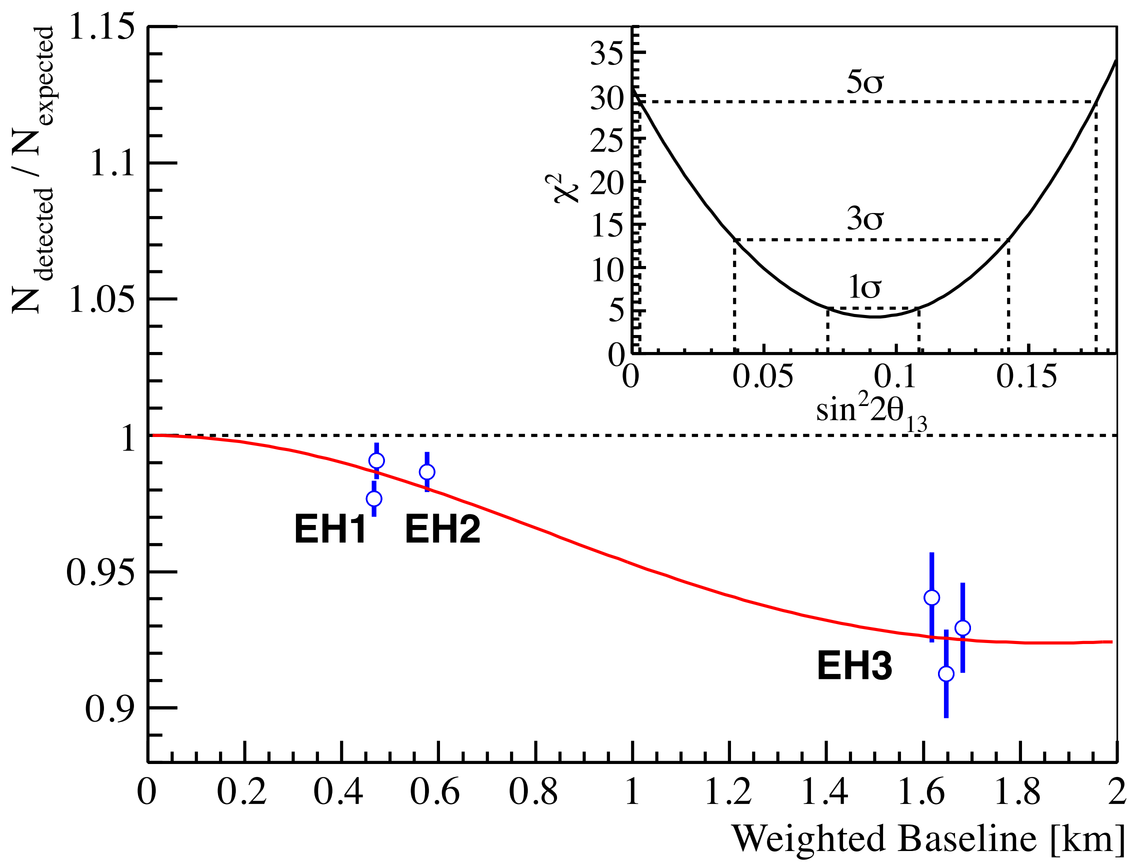


Observation of Electron-antineutrino Disappearance at Daya Bay

Chao Zhang

on behalf of the Daya Bay collaboration

BNL Seminar, 3/8/2012

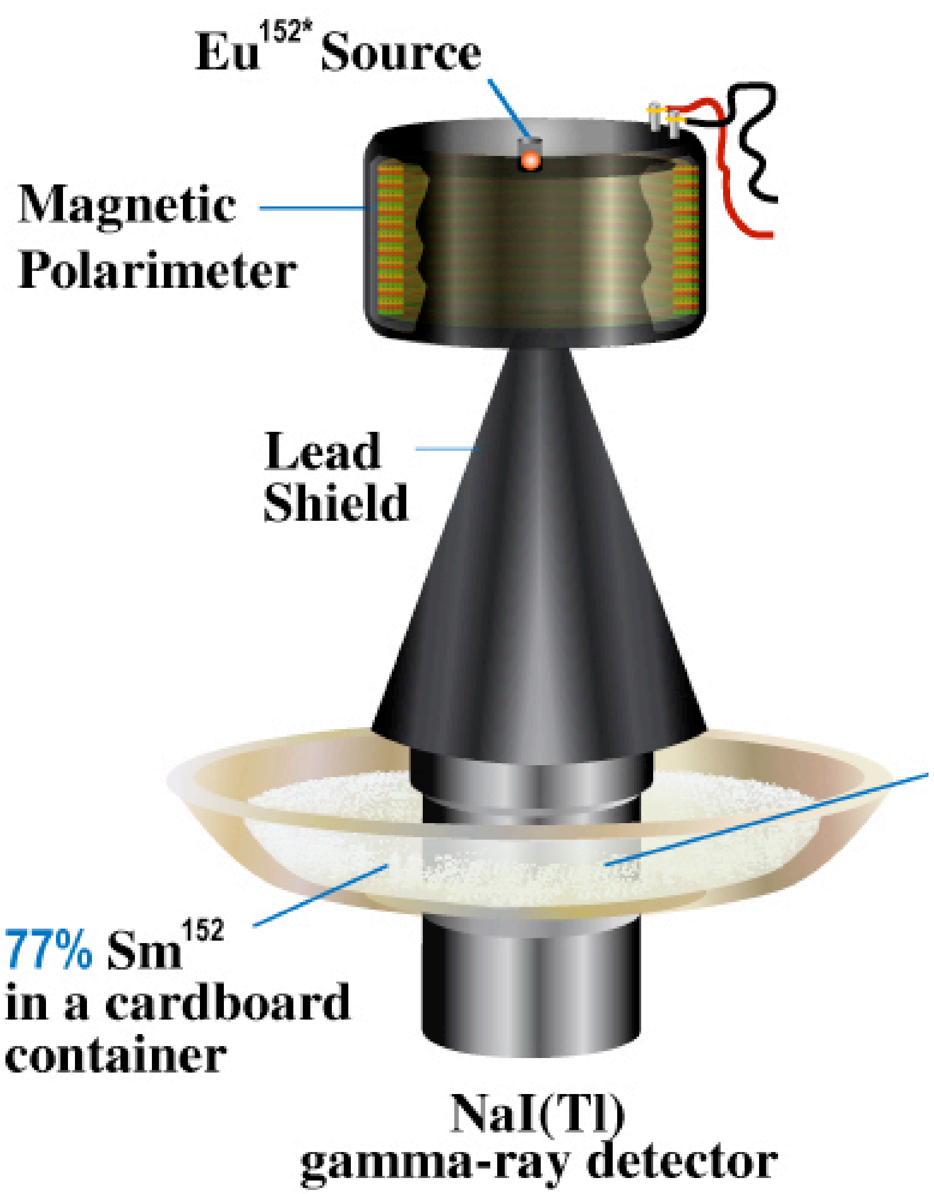
BNL's Highlights in Neutrino Physics

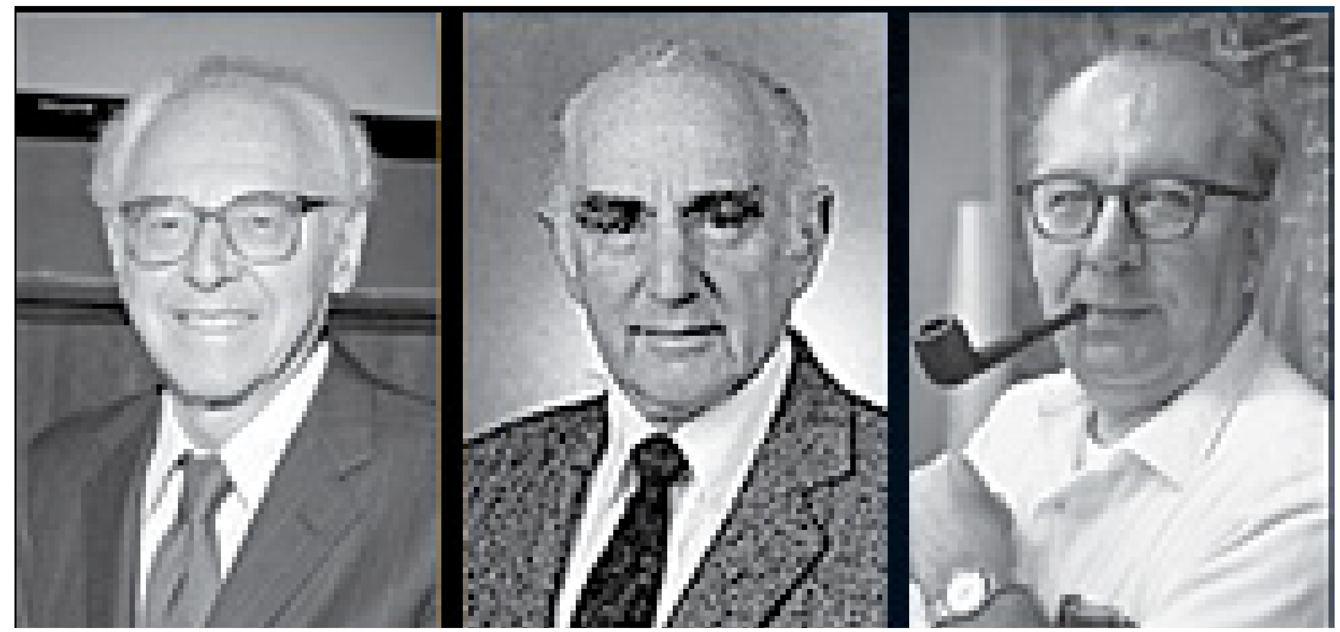
- Over the past 50+ years

Neutrinos Are Left Handed

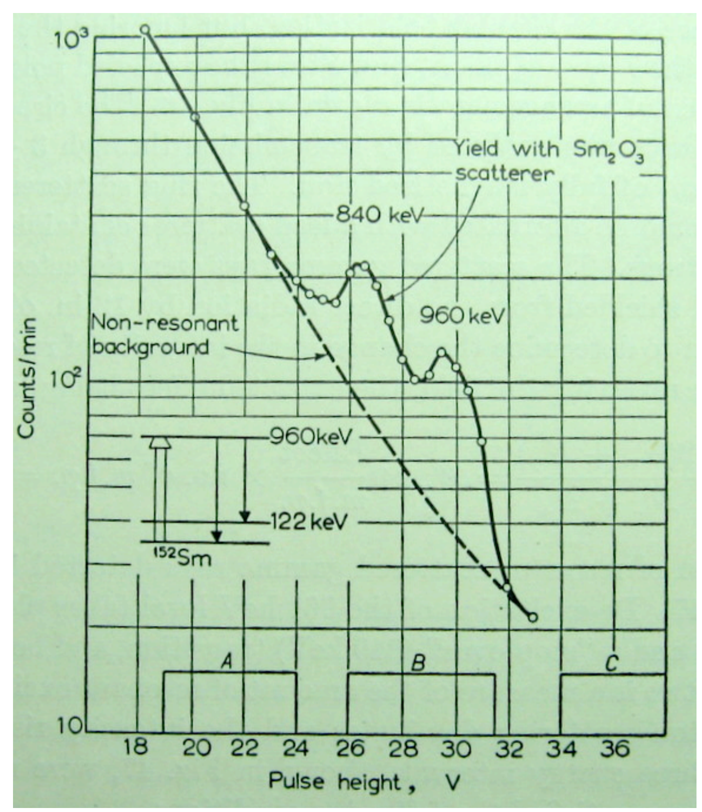
Helicity of Neutrinos*

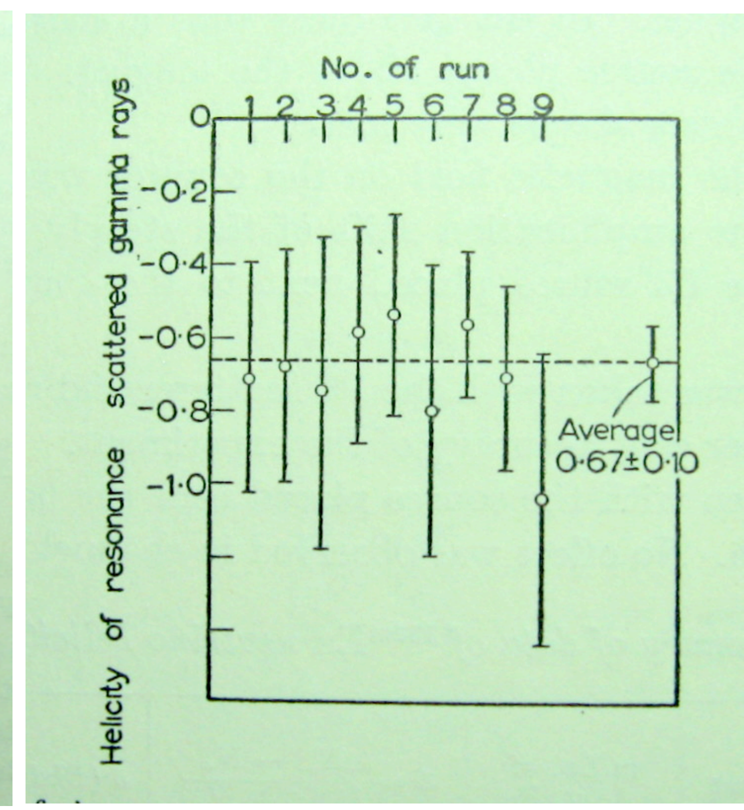
M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)





Maurice Goldhaber Lee Grodzins Andrew Sunyar





More Than One Flavor of Neutrinos

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

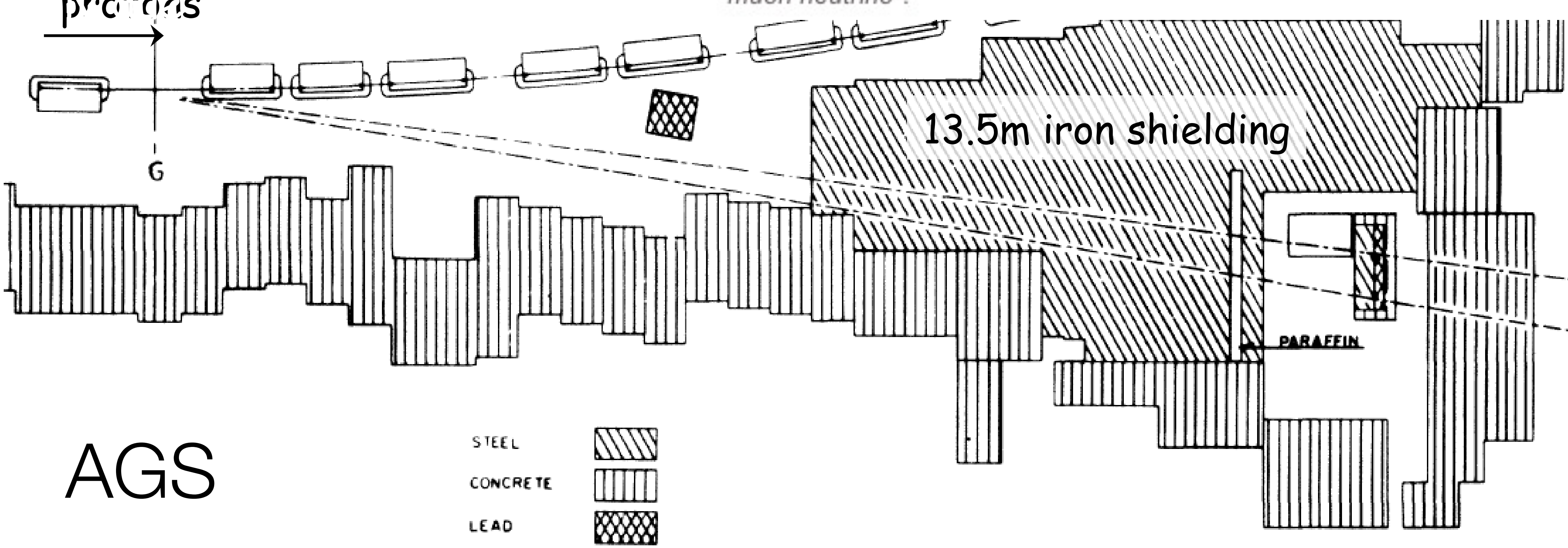
G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

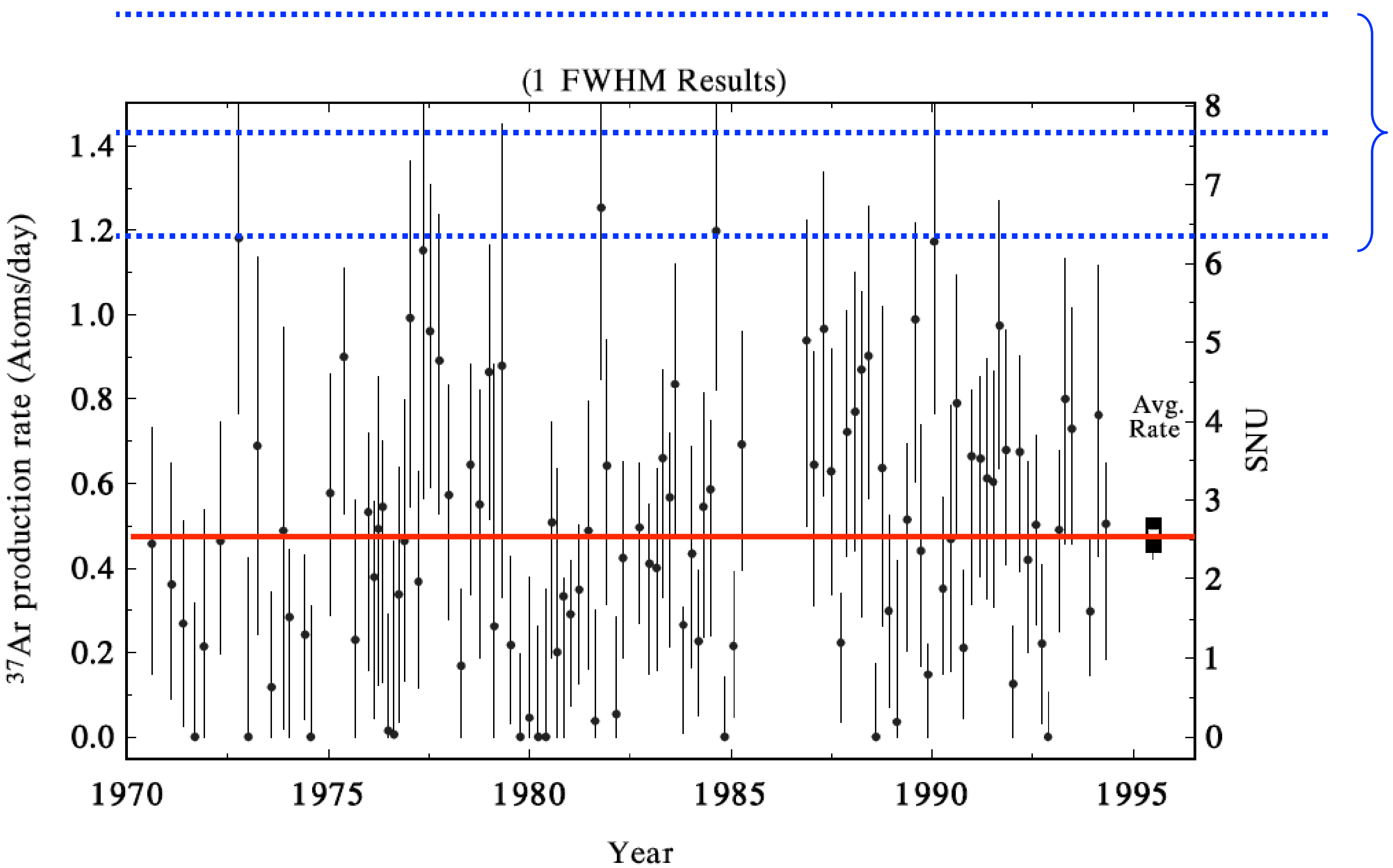
Leon M. Lederman | Melvin Schwartz | Jack Steinberger

The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"*.



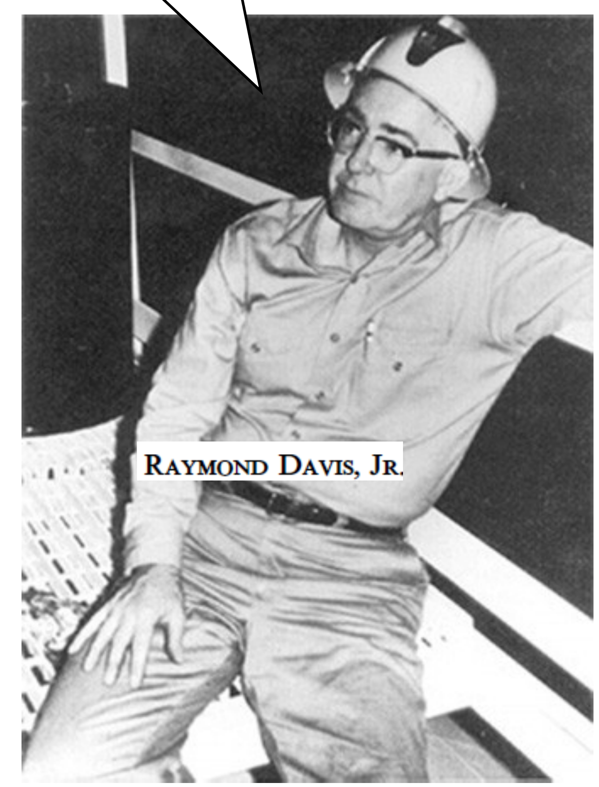
AGS

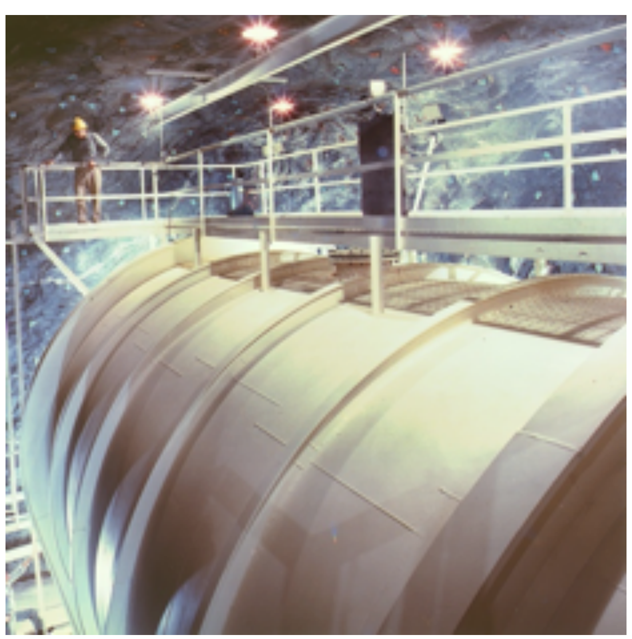
The Missing Solar Neutrinos



Expected rate of ν_e from the sun

Some of the ν_e from the sun are missing.



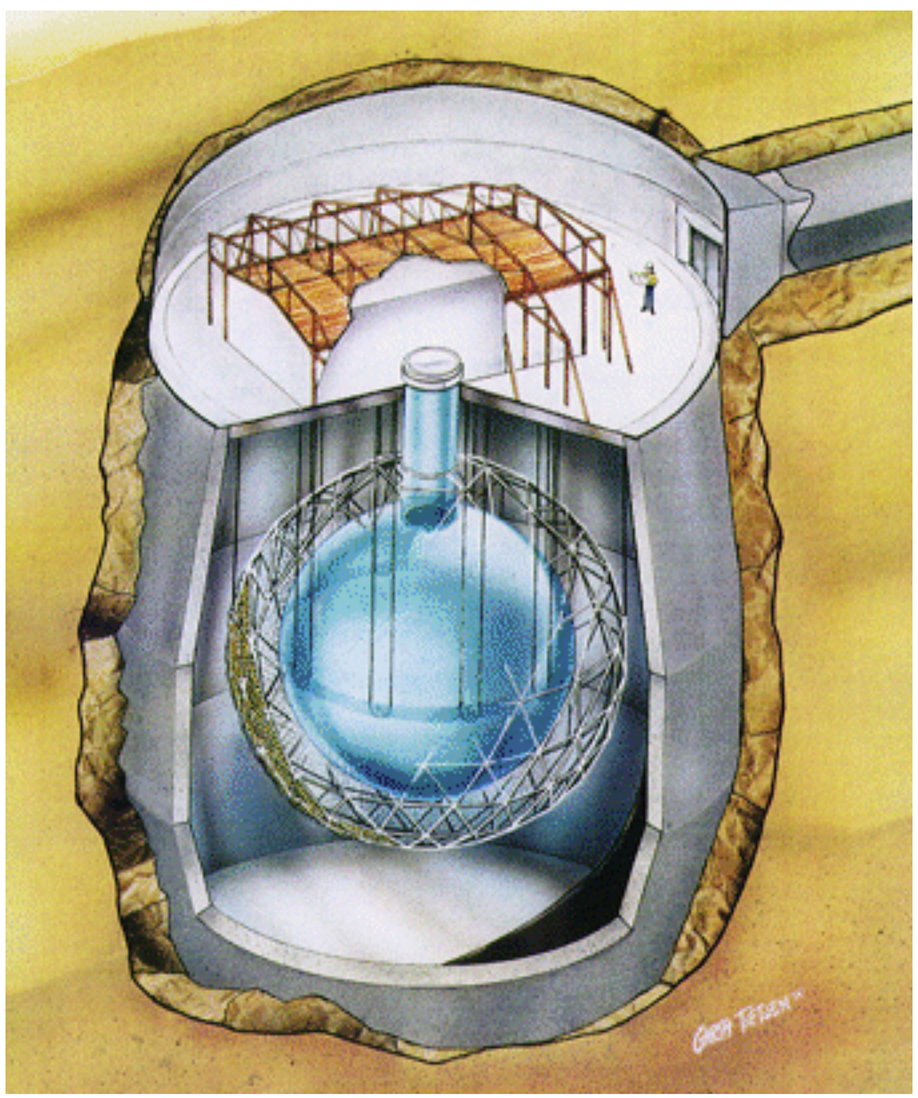


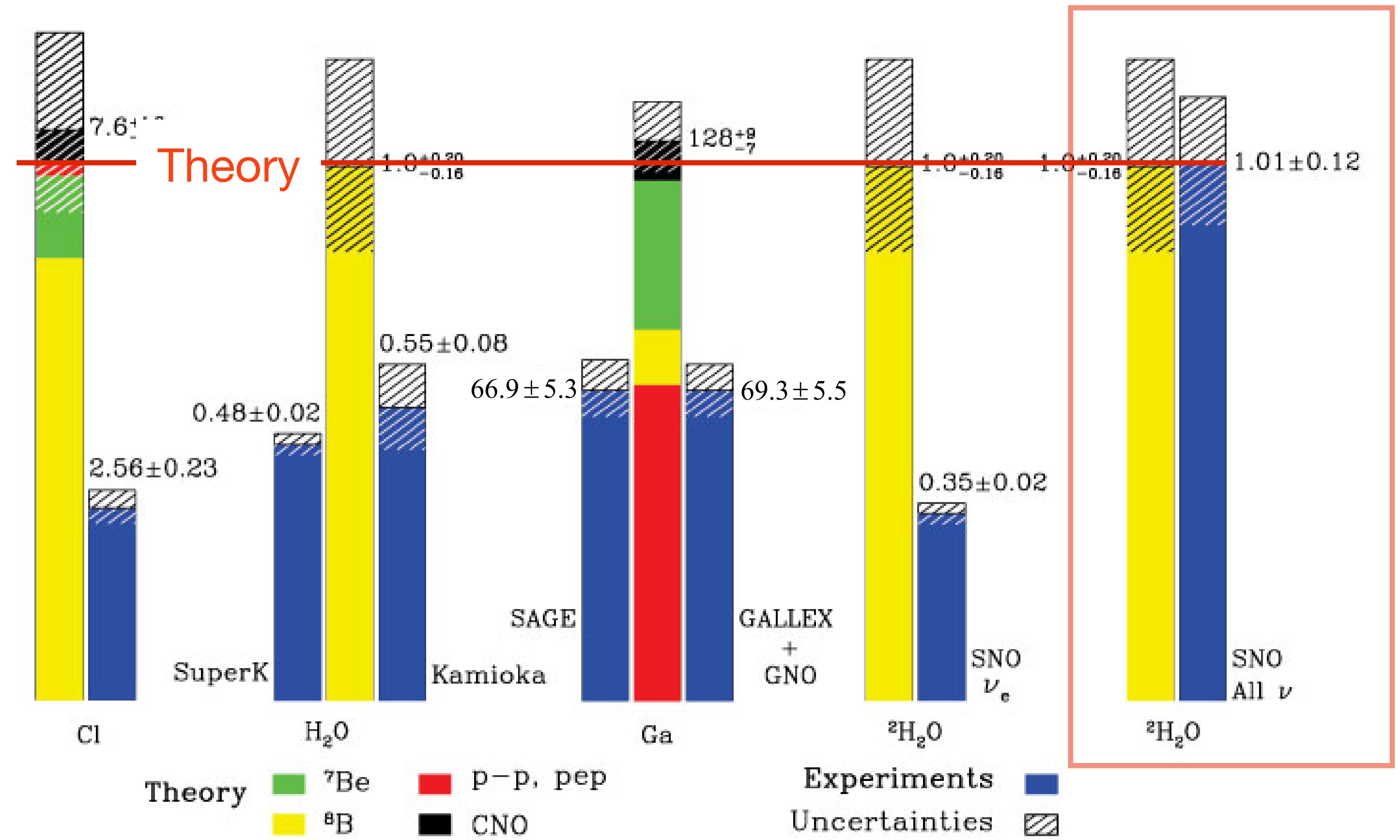
The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

Are Due to Neutrino Oscillation

SNO

BNL: Richard L. Hahn's group





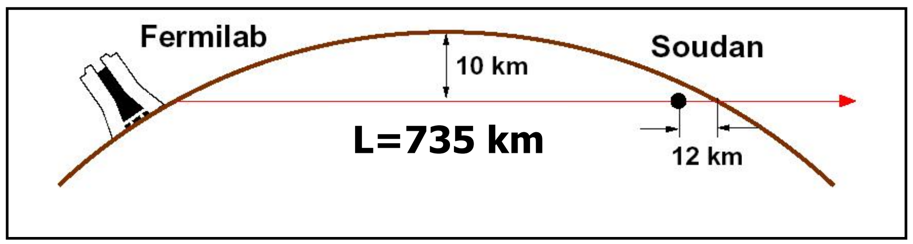
ν_e missing

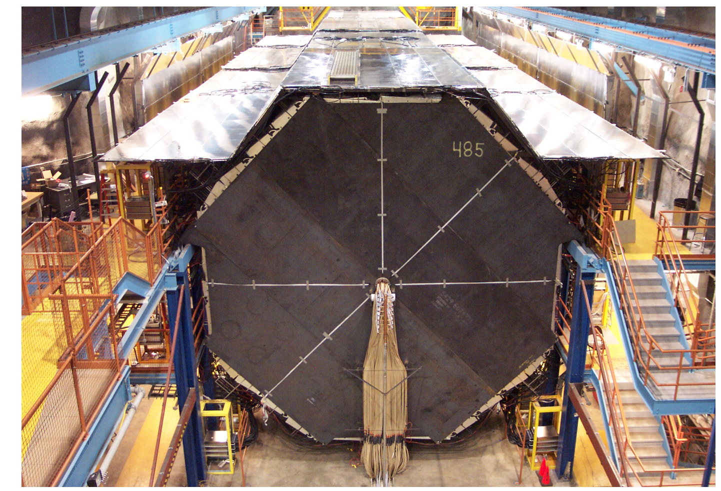
but $\nu_e + \nu_\mu + \nu_\tau$ agree

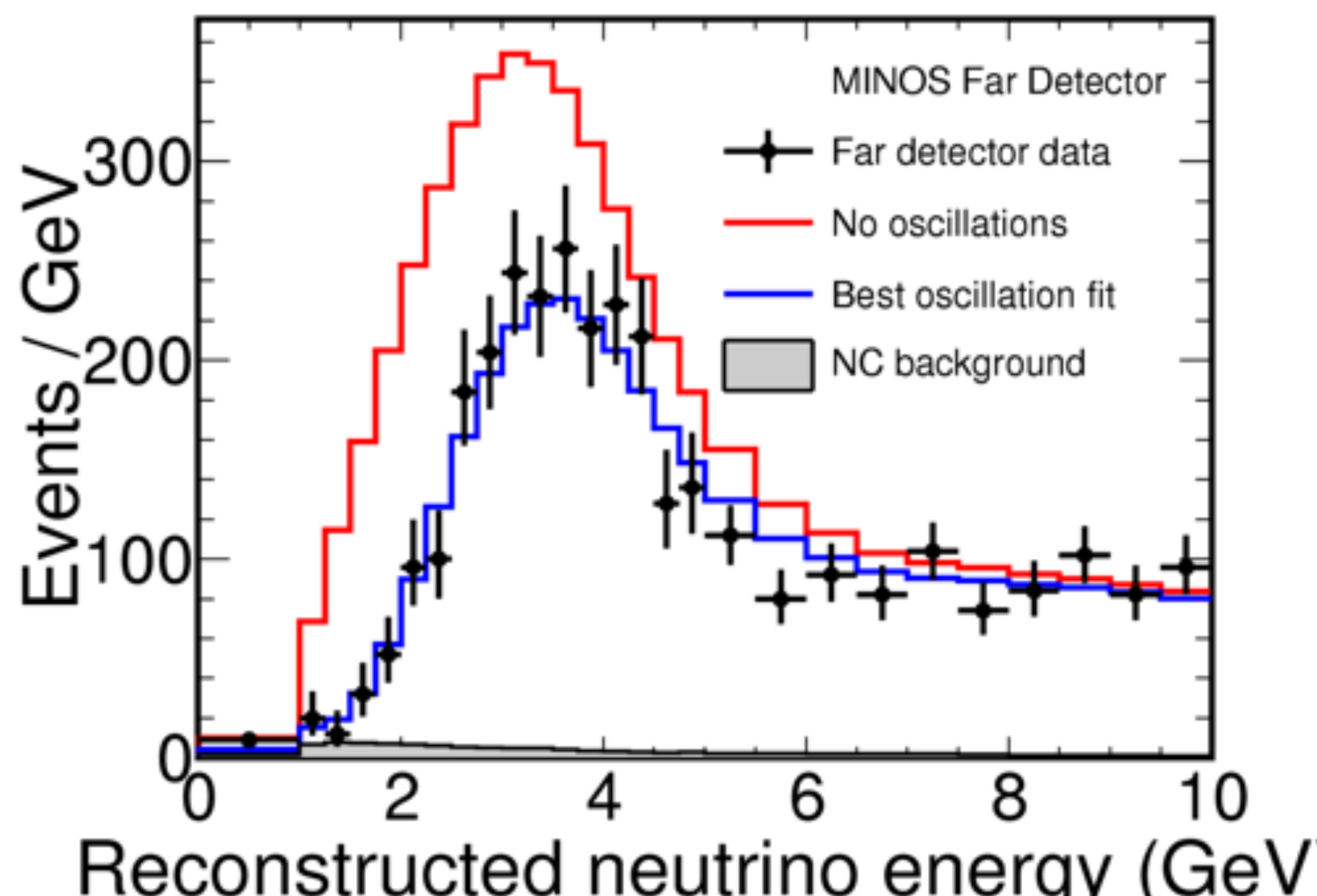
The Missing Accelerator Neutrinos

MINOS

BNL: Milind Diwan's group

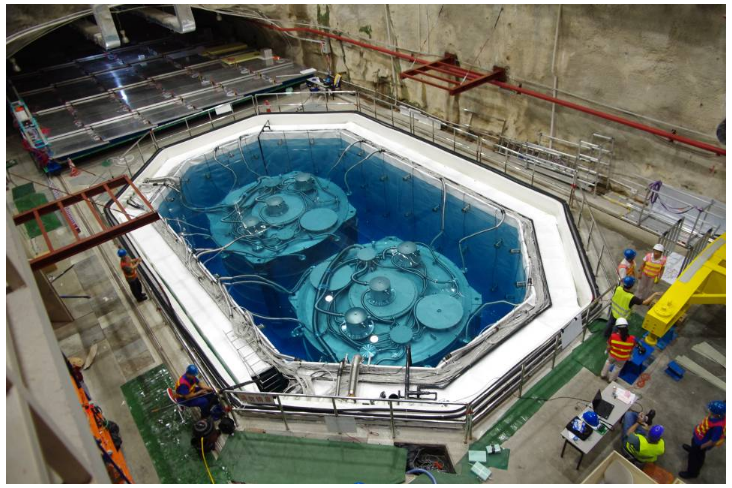


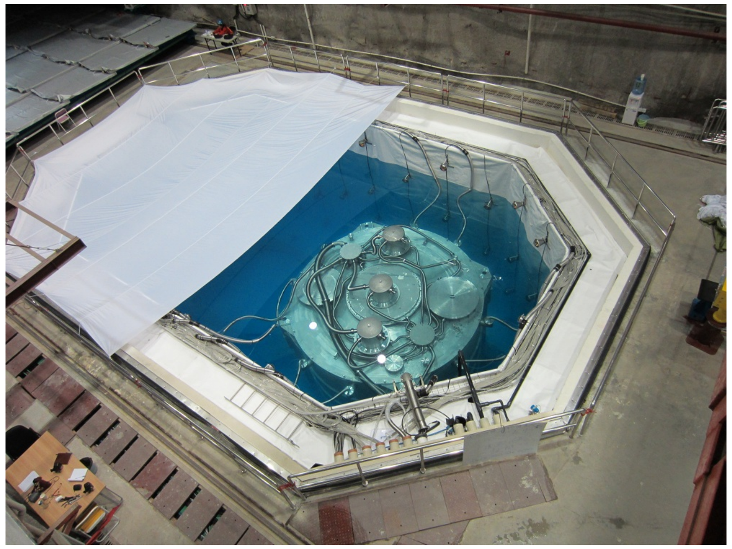


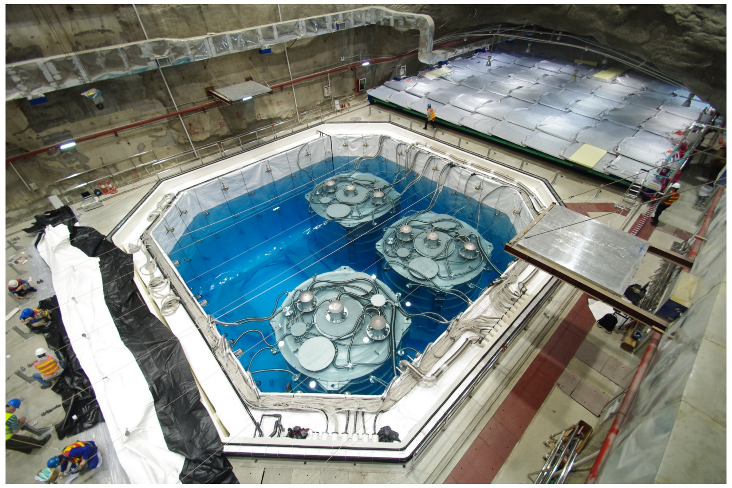


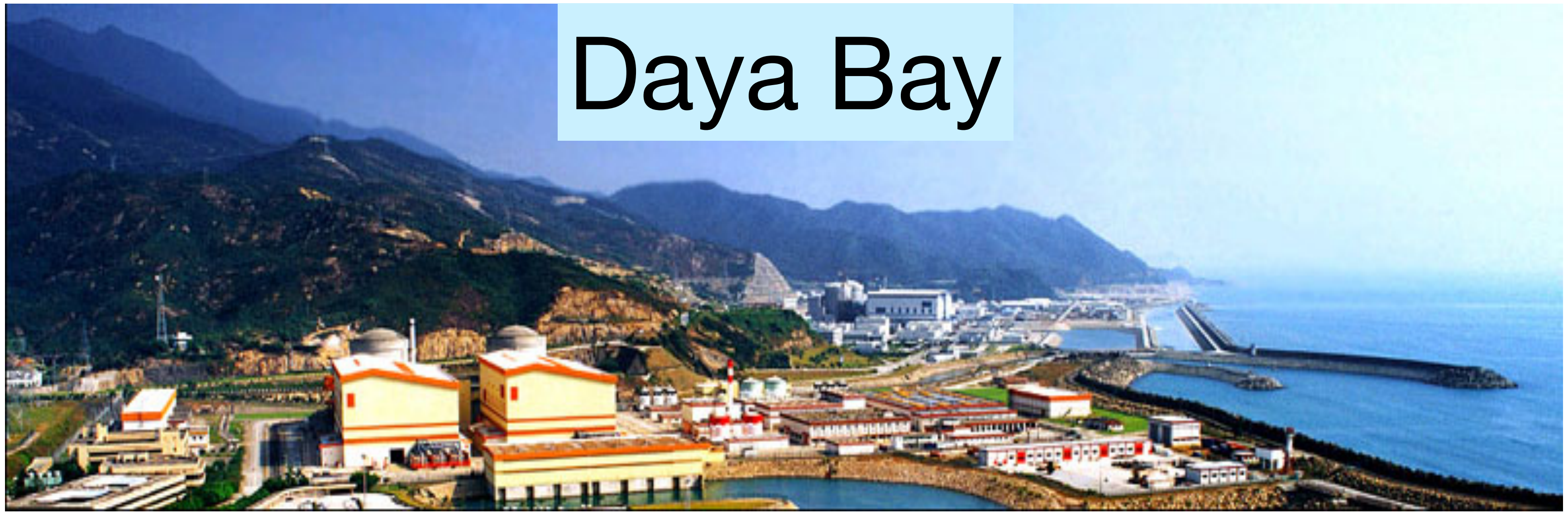
Now We Can Add to The Long History ...

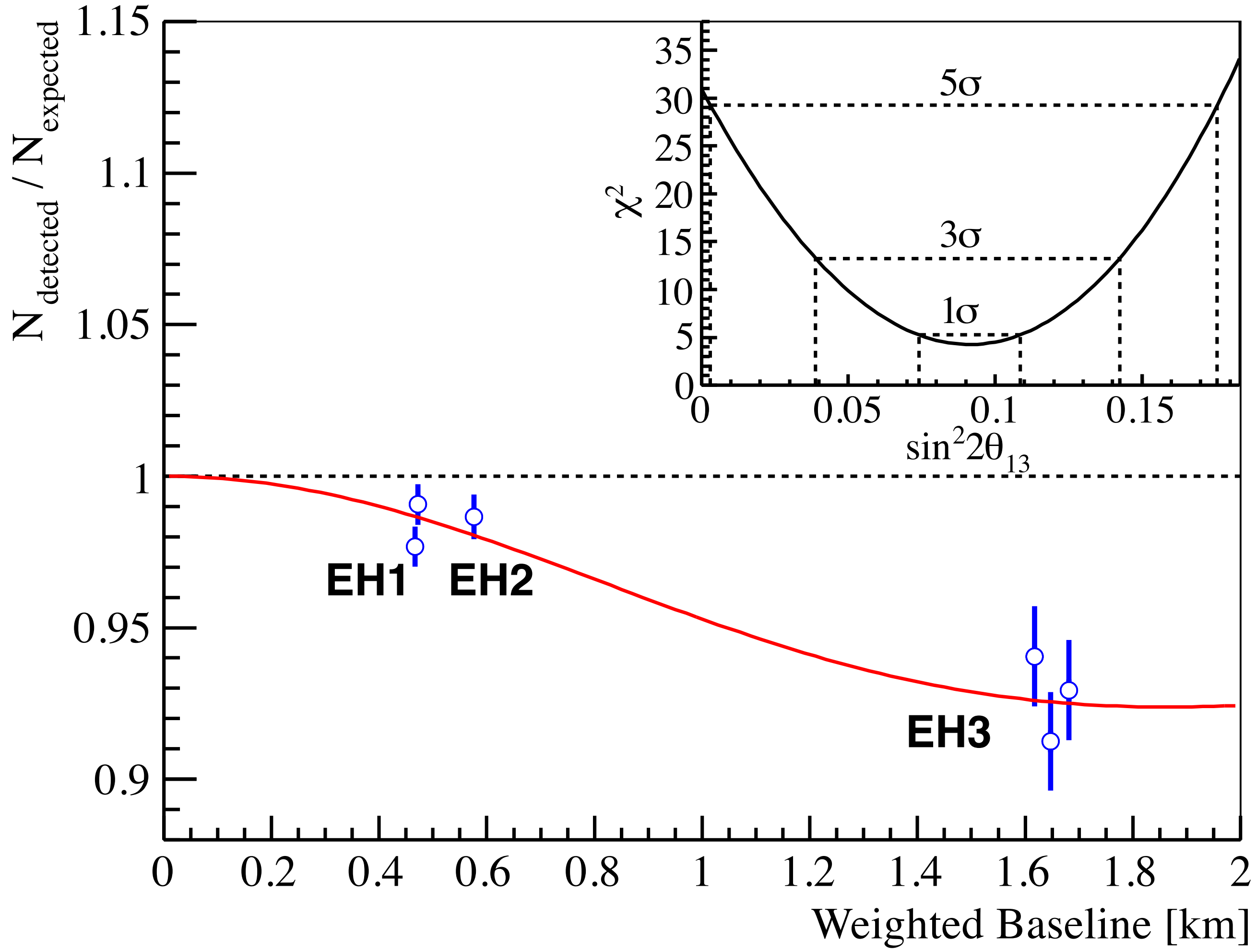
The Missing Reactor Neutrinos





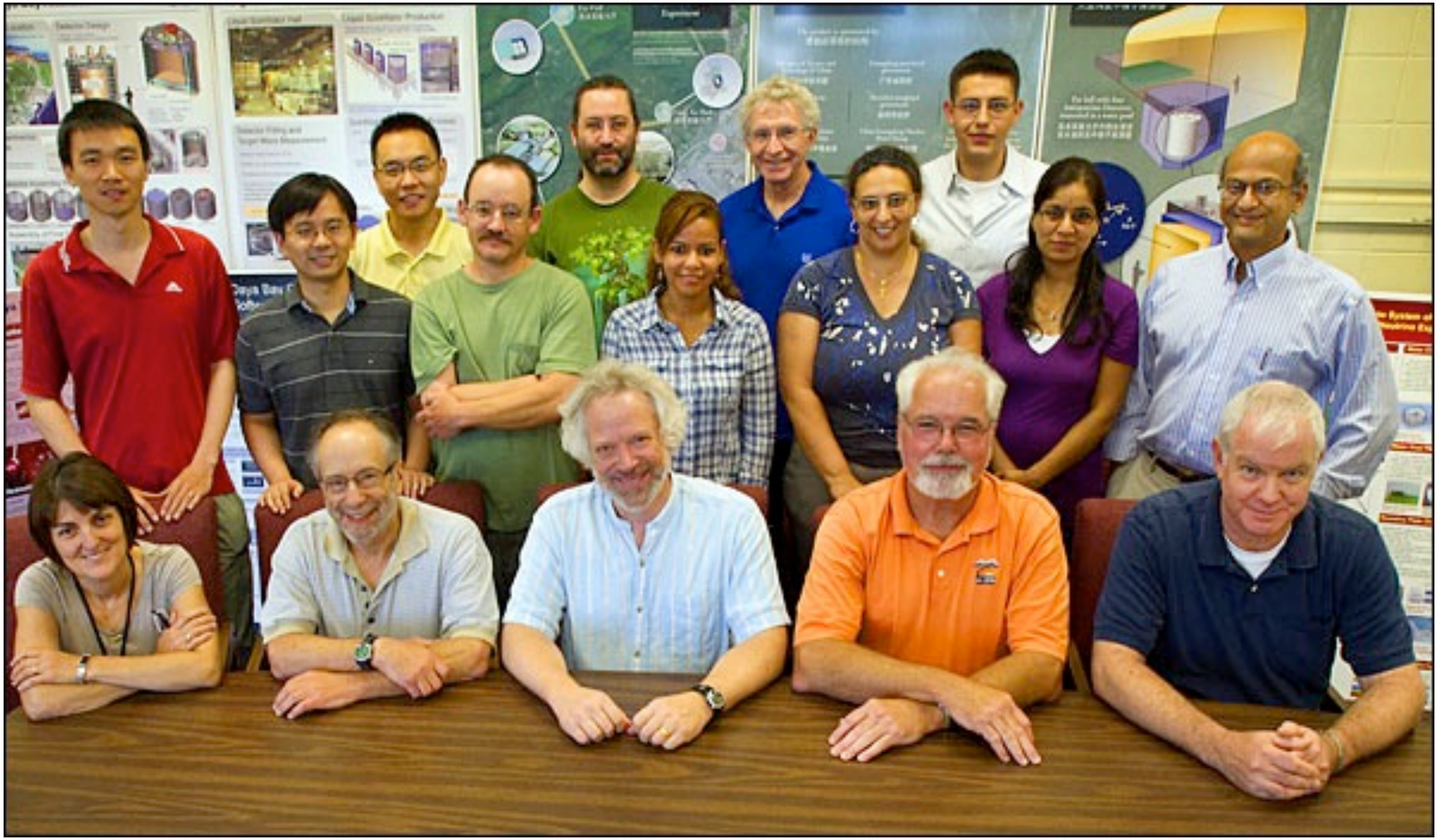






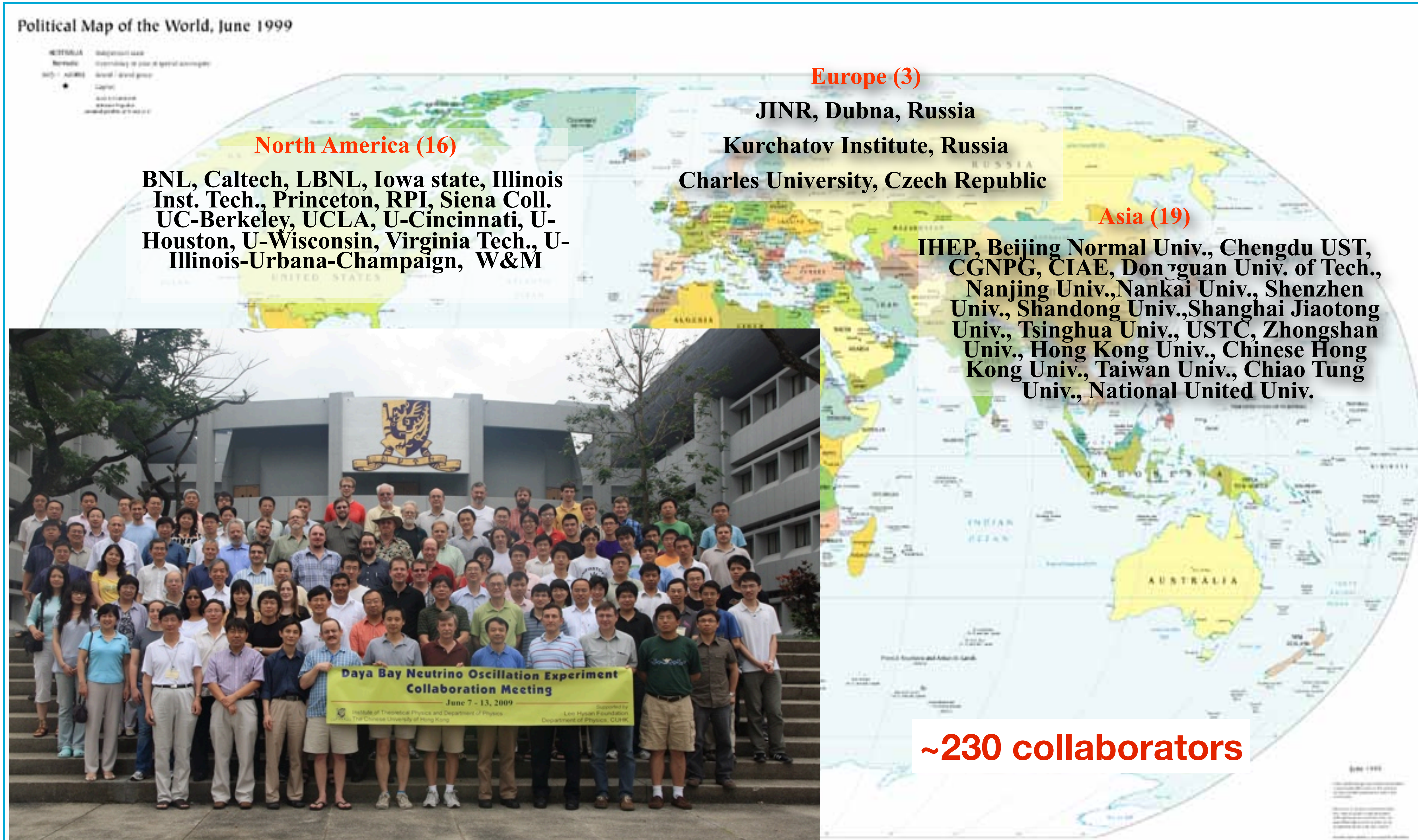
Thanks to ...

The BNL Group on Daya Bay



Members of the BNL team on the Daya Bay Neutrino Project include: (seated, from left) Penka Novakova, Laurie Littenberg, Steve Kettell, Ralph Brown, and Bob Hackenburg; (standing, from left) Zhe Wang, Chao Zhang, Jiajie Ling, David Jaffe, Brett Viren, Wanda Beriguete, Ron Gill, Mary Bishai, Richard Rosero, Sunej Hans, and Milind Diwan. Missing from the picture are: Donna Barci, Wai-Ting Chan, Chellis Chasman, Debbie Kerr, Hide Tanaka, Minfang Yeh, and Elizabeth Worcester, Harry Themann and Zeynep Isvan.

The Daya Bay Collaboration



North America (16)

BNL, Caltech, LBNL, Iowa state, Illinois Inst. Tech., Princeton, RPI, Siena Coll. UC-Berkeley, UCLA, U-Cincinnati, U-Houston, U-Wisconsin, Virginia Tech., U-Illinois-Urbana-Champaign, W&M

Europe (3)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

Asia (19)

IHEP, Beijing Normal Univ., Chengdu UST, CGNPG, CIAE, Dongguan Univ. of Tech., Nanjing Univ.,Nankai Univ., Shenzhen Univ., Shandong Univ.,Shanghai Jiaotong Univ., Tsinghua Univ., USTC, Zhongshan Univ., Hong Kong Univ., Chinese Hong Kong Univ., Taiwan Univ., Chiao Tung Univ., National United Univ.

~230 collaborators

The Hunt For θ$_{13}$

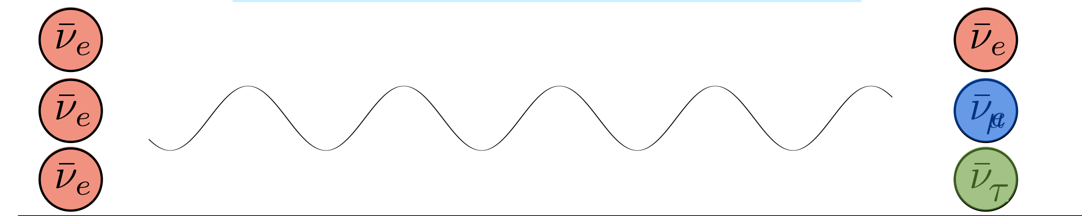
neutrino weak eigenstate ≠ mass eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\downarrow$$

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Neutrino Oscillation



θ12 ~ 35°
Solar ν
Long-Baseline Reactor ν

θ13 < 10°
Short-Baseline Reactor ν
Accelerator ν

θ23 ~ 45°
Atmospheric ν
Accelerator ν

Or big?

θ$_{13}$ is the least known mixing angle

Is it tiny?

Recent Hints of non-zero θ_{13}

Year 2011 has given many hints

T2K

$$0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$$

θ_{13}=0 disfavored @ 2.5σ

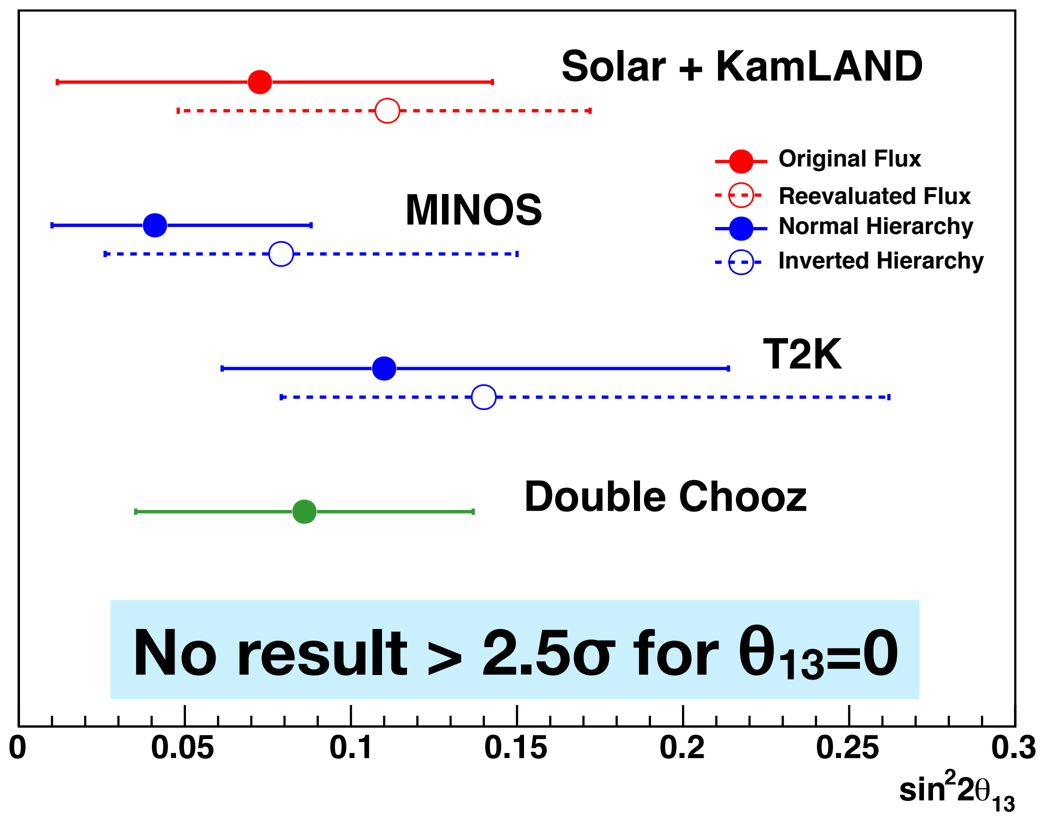
MINOS

$$2\sin^2(\theta_{23})\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$$

θ_{13}=0 disfavored @ 89% C.L.

Double Chooz

$\sin^2(2\theta_{13})$=0.086
± 0.041(stat) ± 0.030(syst)

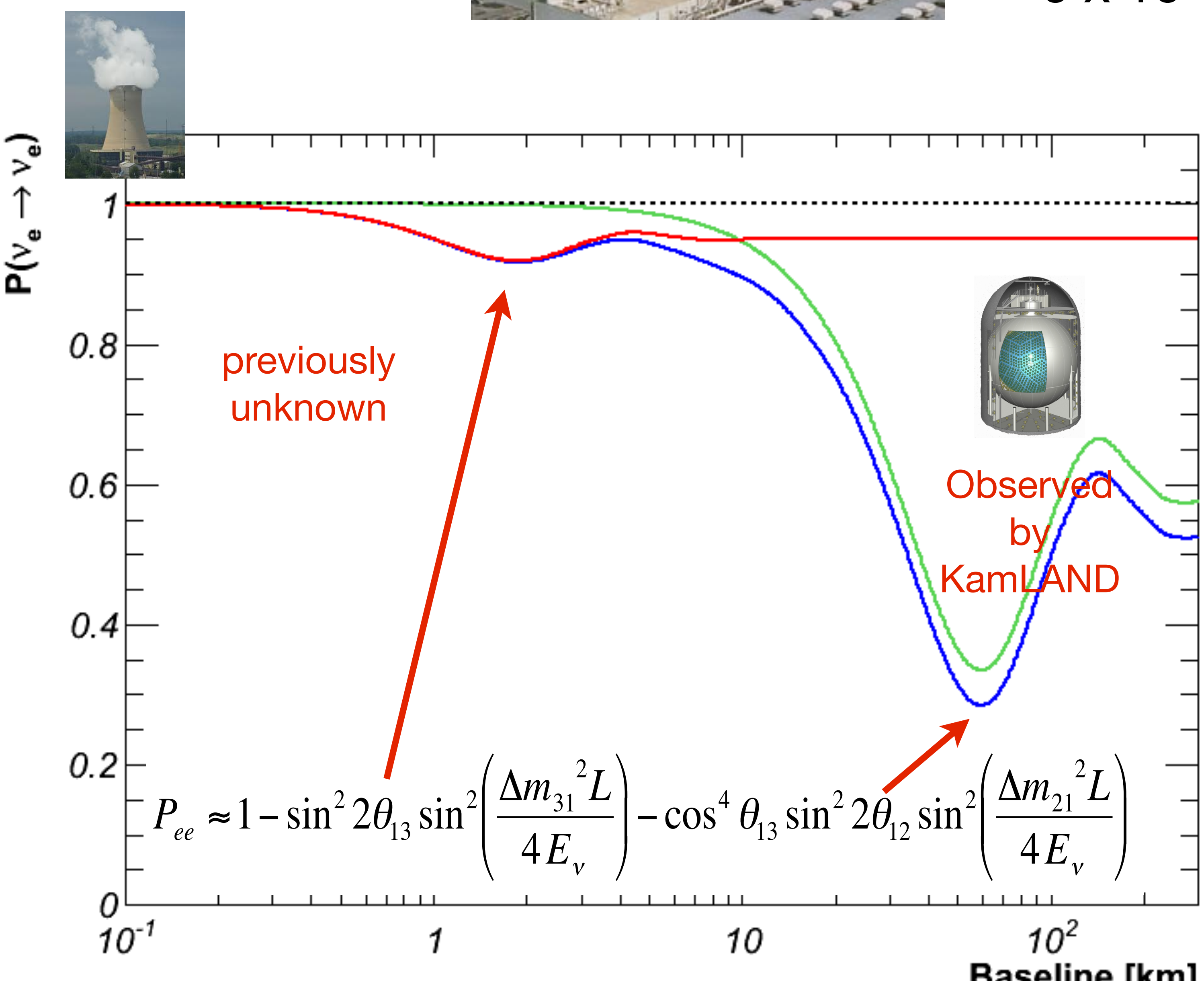


A definitive precision experiment is needed.
How can Daya Bay do better?

Reactor vs. Accelerator

Nuclear Reactor

- pure $\bar{\nu}_e$ source
- 6 $\bar{\nu}_e$ / fission
- 6 x 10^{20} $\bar{\nu}_e$ / sec / 3GW$_{th}$

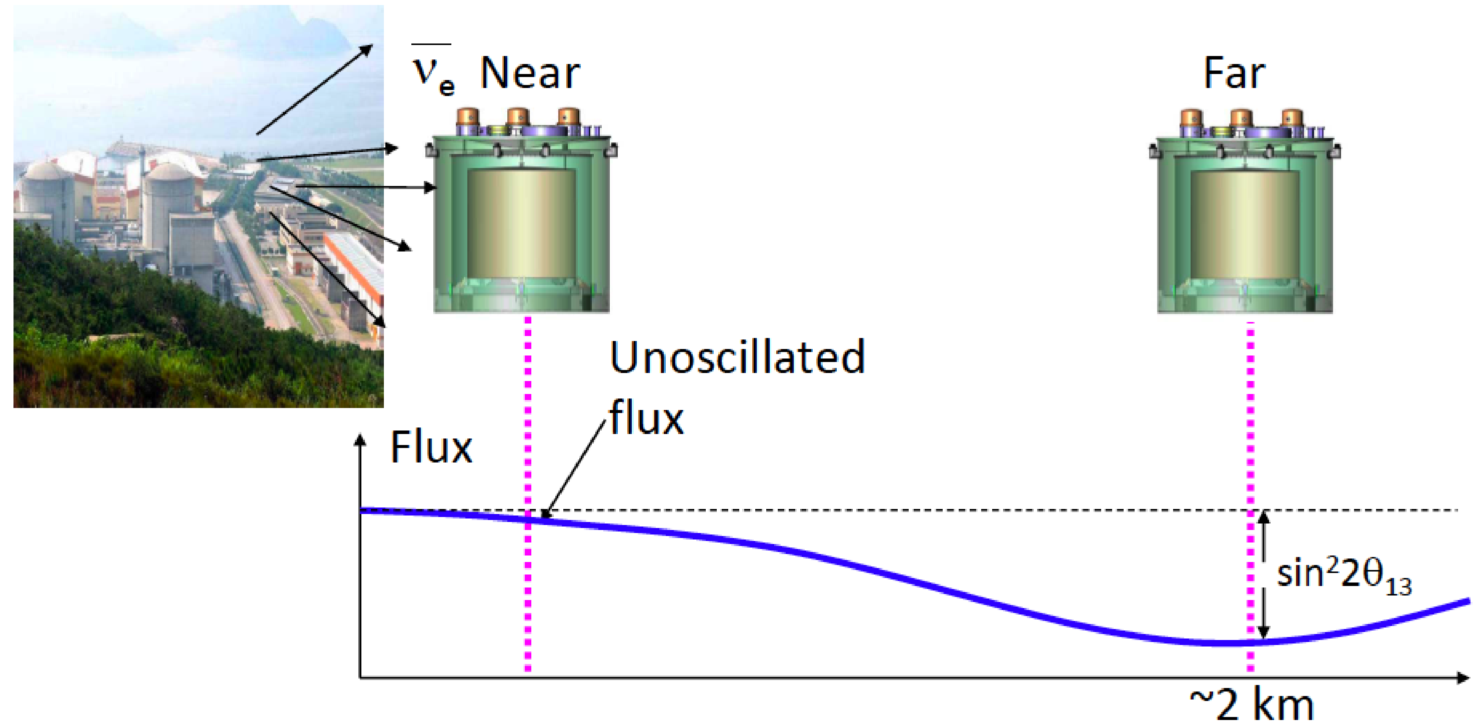


Benefits of reactor neutrinos

- Free neutrinos! Large statistics
- Clean detection signal
- No CP violation
- Negligible matter effects

Far / Near Relative Measurements

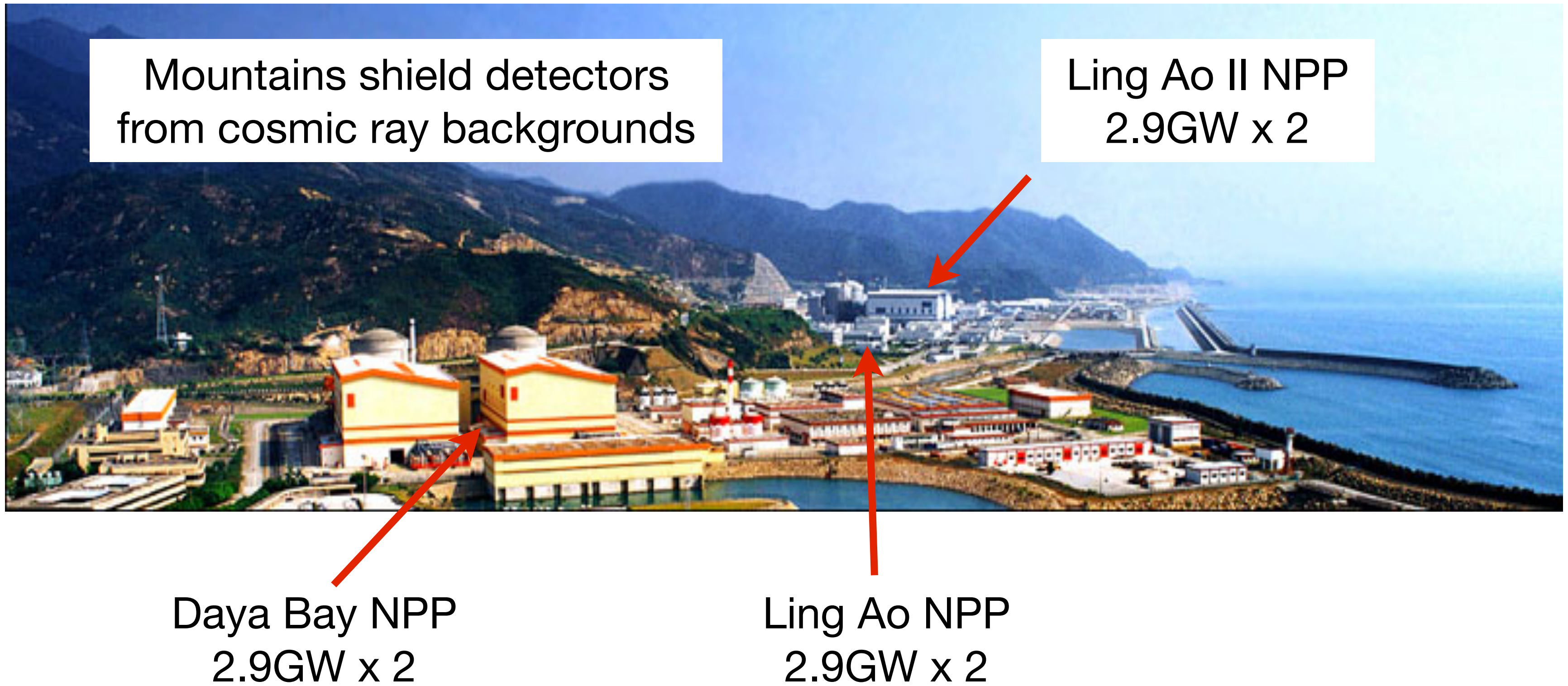
- Far/Near measurements, knowledge of the absolute rate of reactor antineutrino is not needed
- ‘Functionally Identical’ detectors to cancel detector related uncertainties



$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

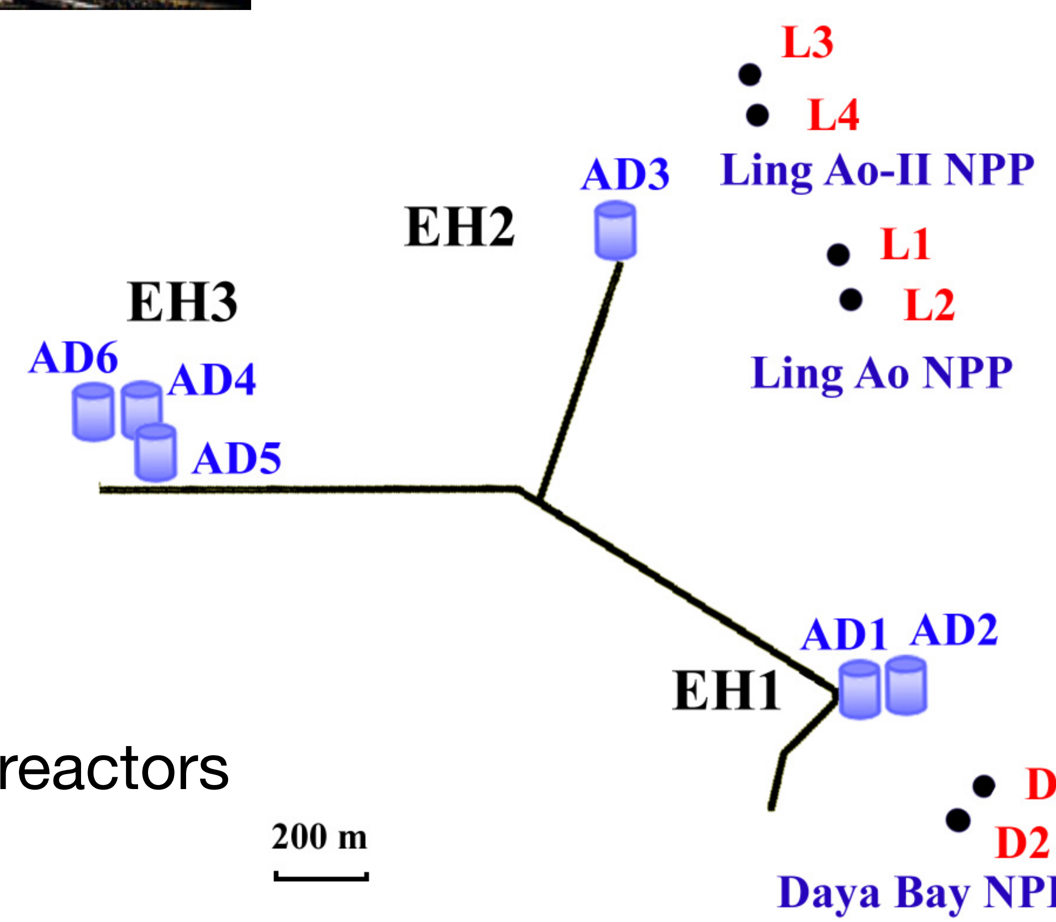
Far/Near Neutrino Ratio | **Detector Target Mass** | **Distance from Reactor** | **Detector Efficiency** | **Survival Probability (θ13)**

Daya Bay: An Ideal Location



	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.



Definition of Terms

EH 1/2/3: Experimental Hall 1/2/3
D1/D2: 2 reactor cores in Daya Bay
L1/L2/L3/L4: 4 reactor cores in Ling Ao
Near Site: EH1 + EH2, ~500m from the nearest reactors
Far Site: EH3, ~1.6 km from all reactors
AD: Antineutrino Detector (20 ton target mass)
6 ADs in the three underground halls

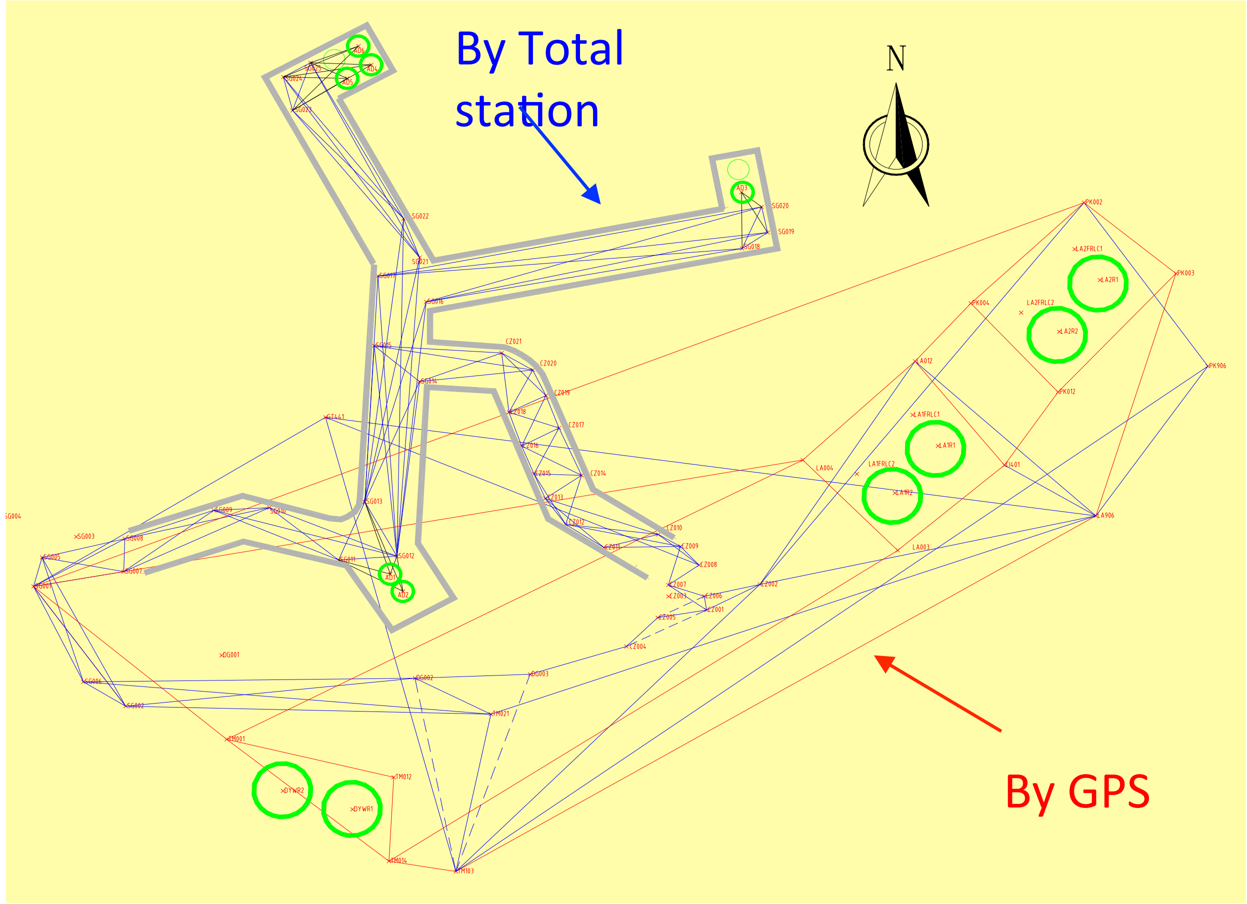
Experiment Survey

Negligible flux uncertainty (<0.02%) from precise survey

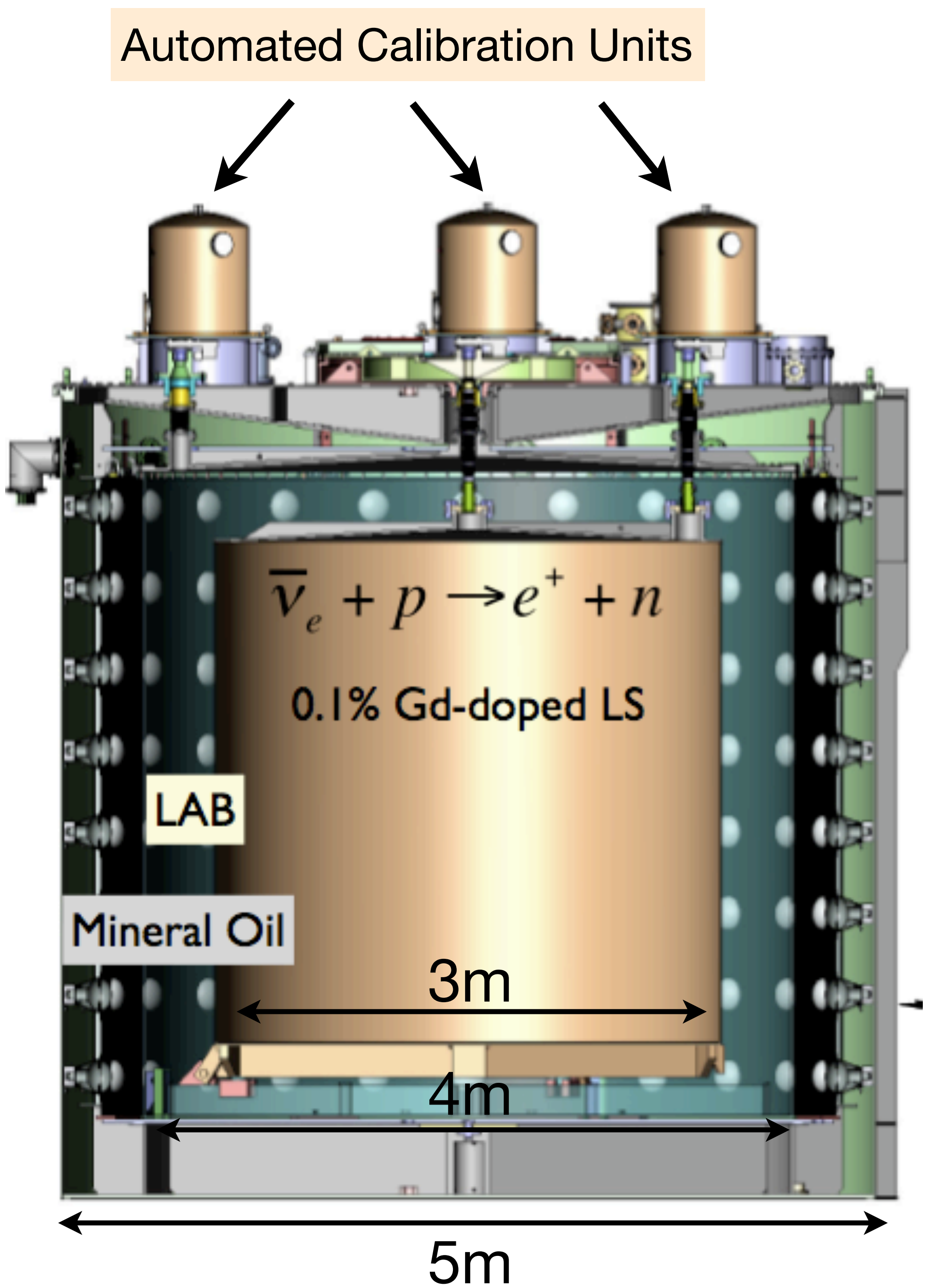
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Detailed Survey:
- GPS above ground
- Total Station underground
- Final precision: 28mm

Validation:
- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans



Anti-neutrino Detector



6 'functionally identical' detectors

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$

Each detector has 3 nested zones separated by Acrylic Vessels:

- Inner: 20 tons Gd-doped LS (target volume)
- Mid: 20 tons LS (gamma catcher)
- Outer: 40 tons mineral oil (buffer)

Each detector has:

- 192 8-inch Photomultipliers (PMTs)
- Optical reflectors at top/bottom of cylinder
- (7.5/√E[MeV] + 0.9)% energy resolution

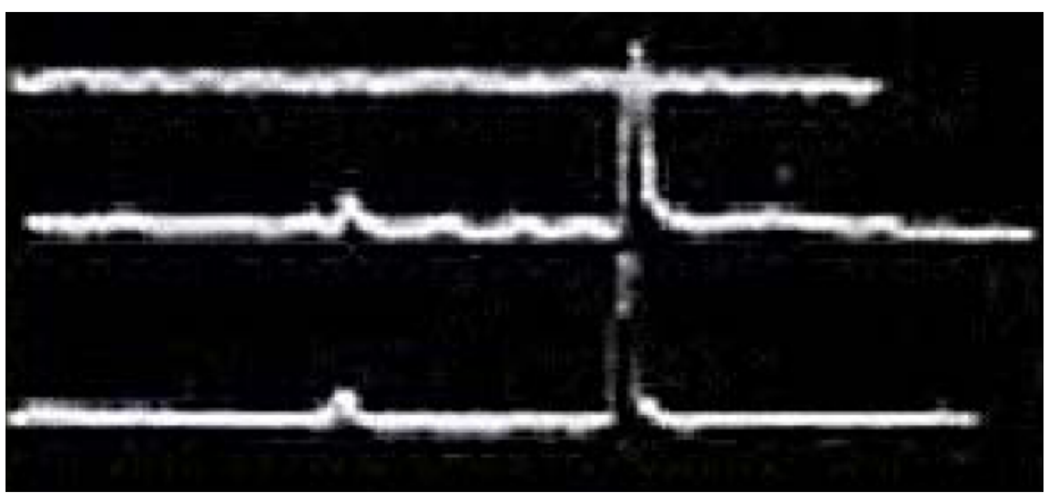
Anti-neutrino Detection Method

Inverse Beta Decay (IBD)

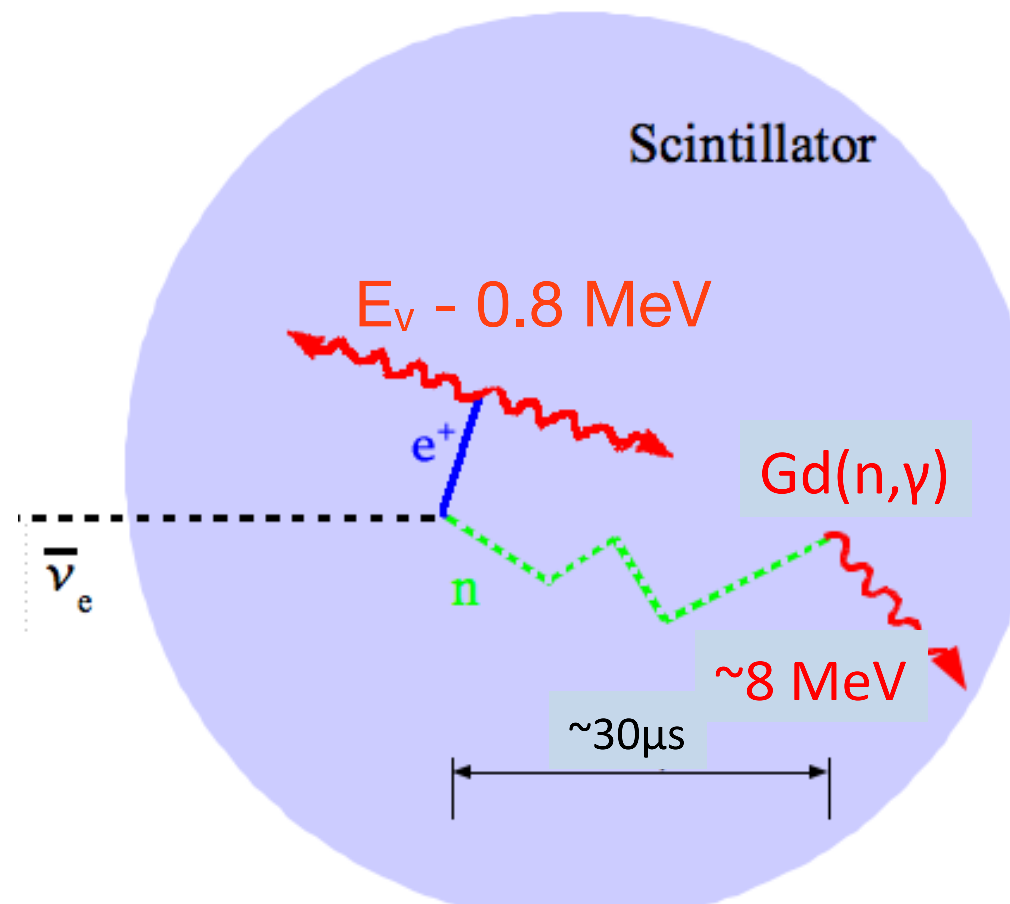
- $E_{threshold}$ = 1.8 MeV
- 'Large' cross section $\sigma \sim 10^{-42}$ cm^2
- Distinctive coincidence signature in a large liquid scintillator detector

$$\bar{\nu}_e + p \rightarrow \boxed{e^+} + n$$

$$\mathrm{n} + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd} + \boxed{\gamma' s}$$

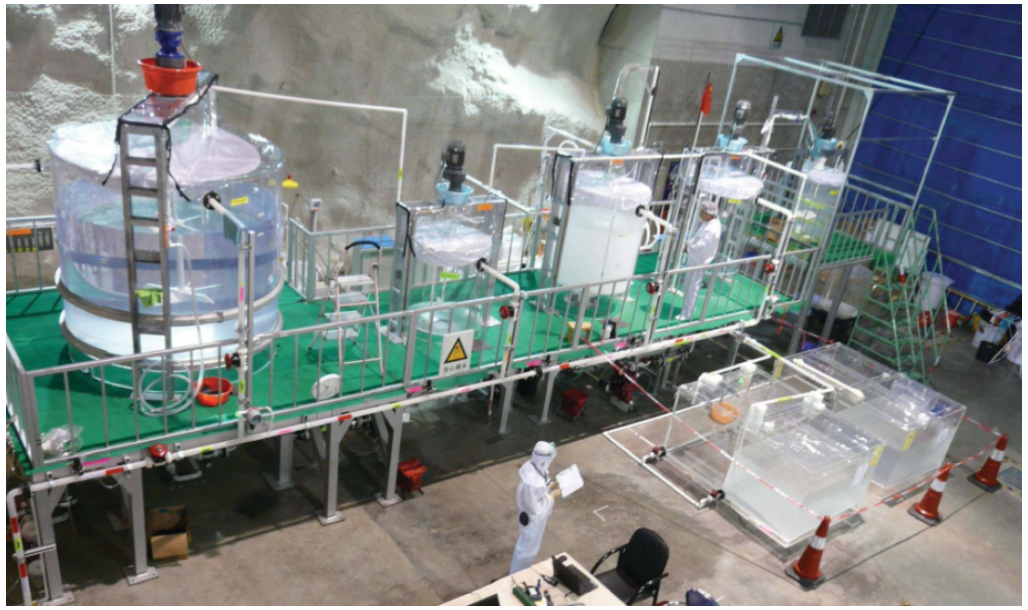


Cowan & Reines, Savannah River 1956



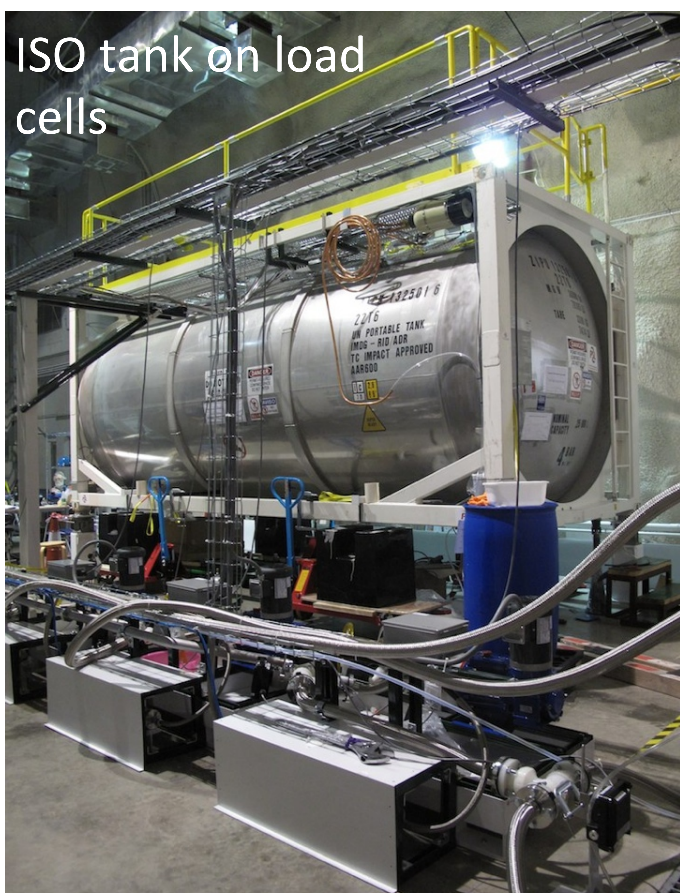
Gd-LS defines the target volume.
Fiducial volume cut is not necessary.

Liquid Production and Filling

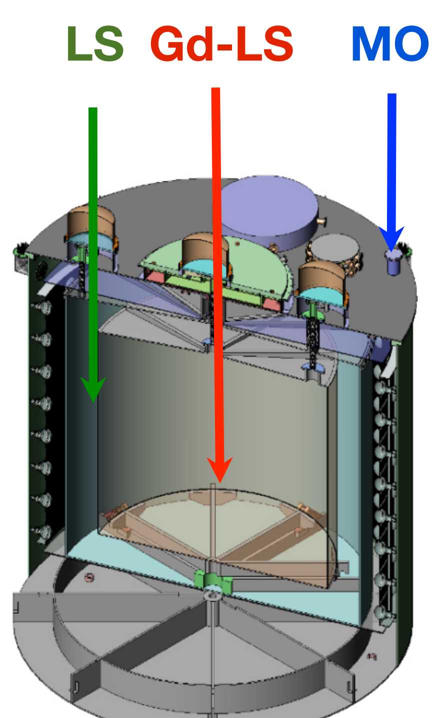


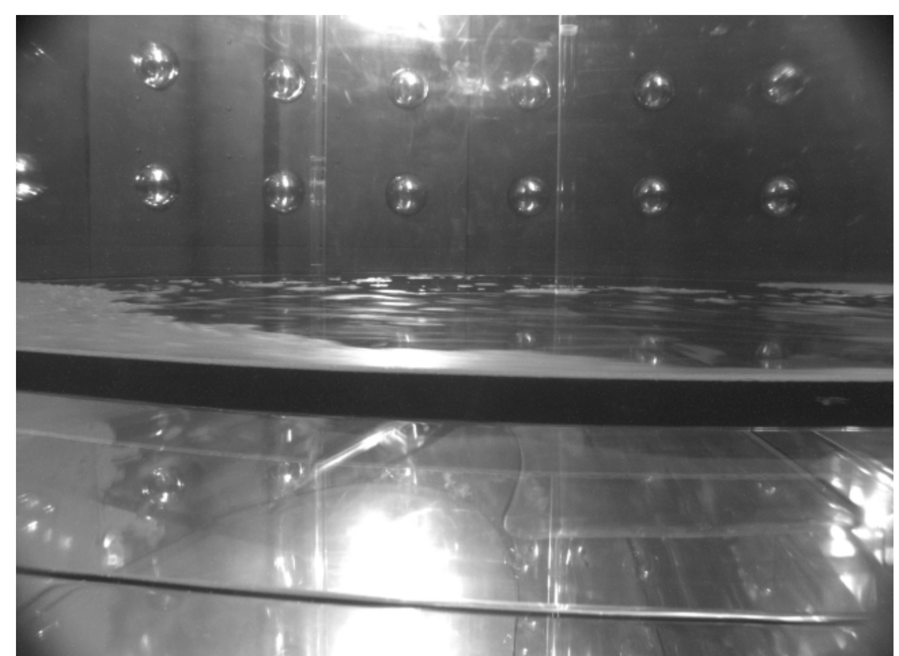
Daya Bay Liquid Scintillator Cocktail

- LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L)
- more than 3 years R&D (BNL & IHEP)
- Multi-stage purifications on optical improvement and U/Th removal
- 185-ton Gd-LS + 196-ton LS production



Load cells measure 20 ton target mass to 3kg (0.015%)

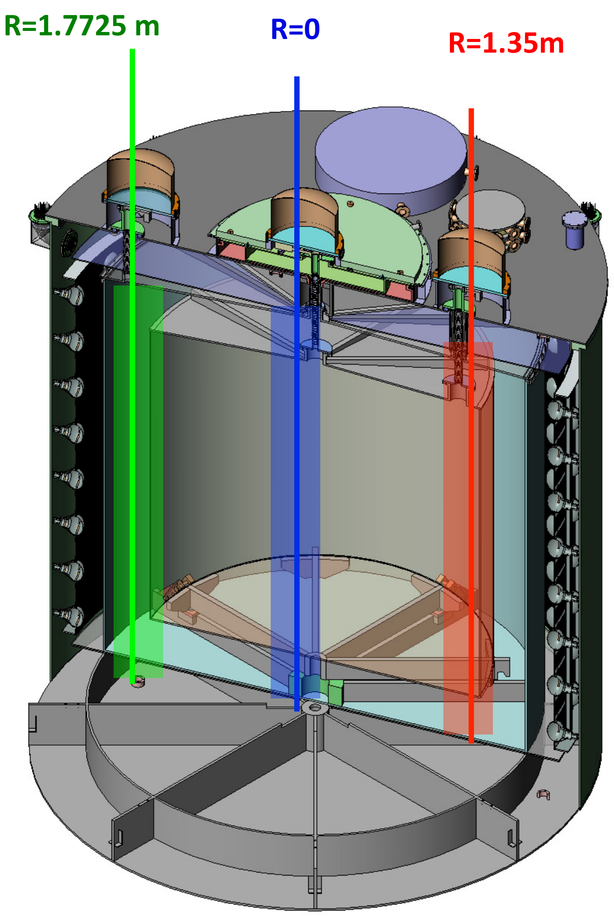




Energy Calibration

3 Automatic Calibration Units (ACUs) on each detector

- 3 ACUs per detector for z-axis deployment (position accuracy < 5 mm)
  - Central Gd-LS
  - Edge Gd-LS
  - LS (gamma catcher)
- Each ACU has three sources on a turntable
  - 10 Hz ^{68}Ge (2 x 0.511 MeV γ's)
  - 0.5 Hz ^{241}Am^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173 + 1.332 MeV γ's)
  - LED diffuser ball for PMT gain and timing
- Simultaneous, automated weekly deployment for all 6 ADs
- Other natural calibration events including spallation neutrons, internal/external γ's and α's from radioactivities



Muon Veto System

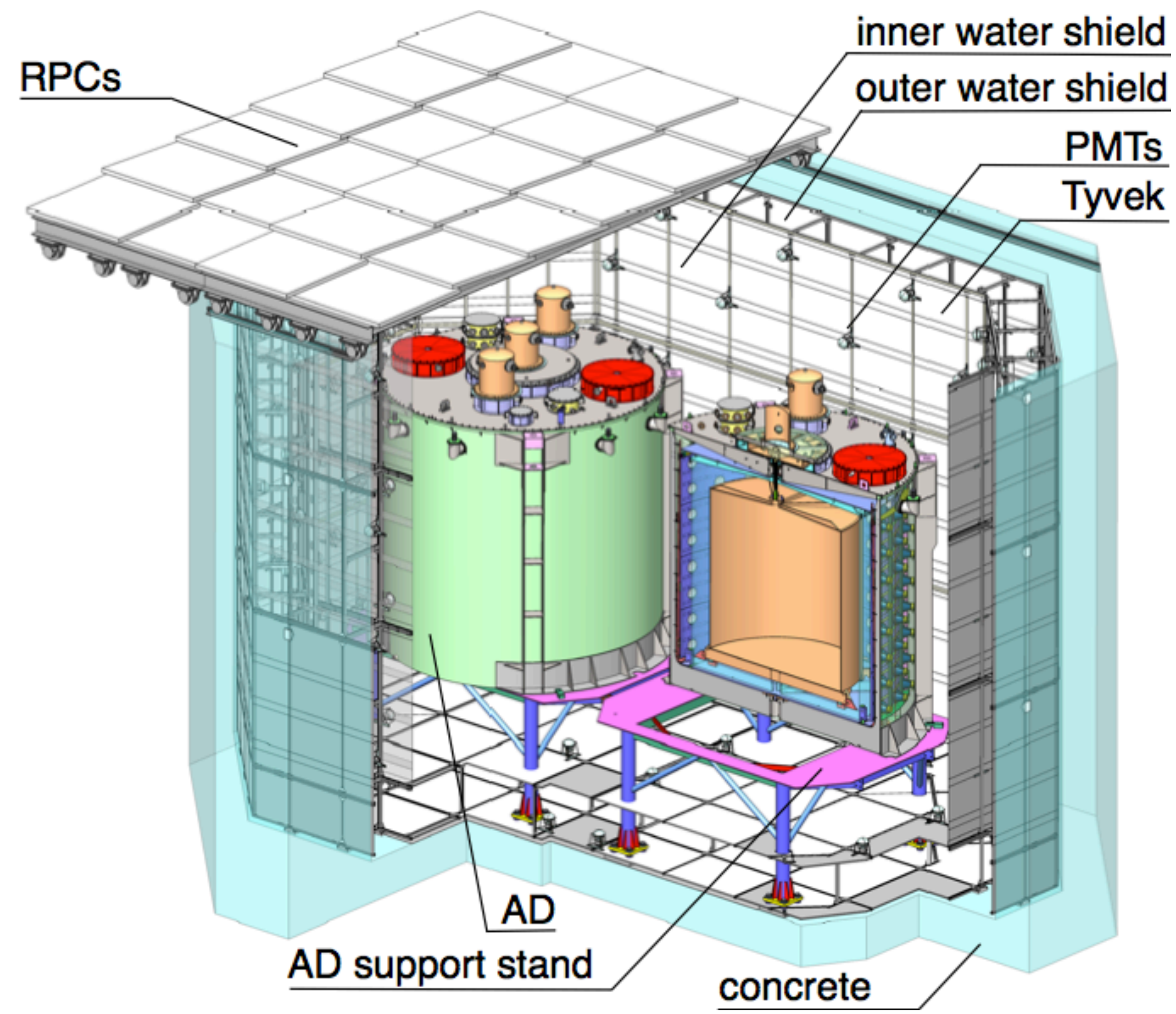
Multiple muon veto detectors
2.5m thick two-sector active water shield and RPC

Water Cherenkov

- Detectors submerged in water shielded against external neutrons and gammas

- Optically separated by Tyvek sheets into inner / outer region for cross-check

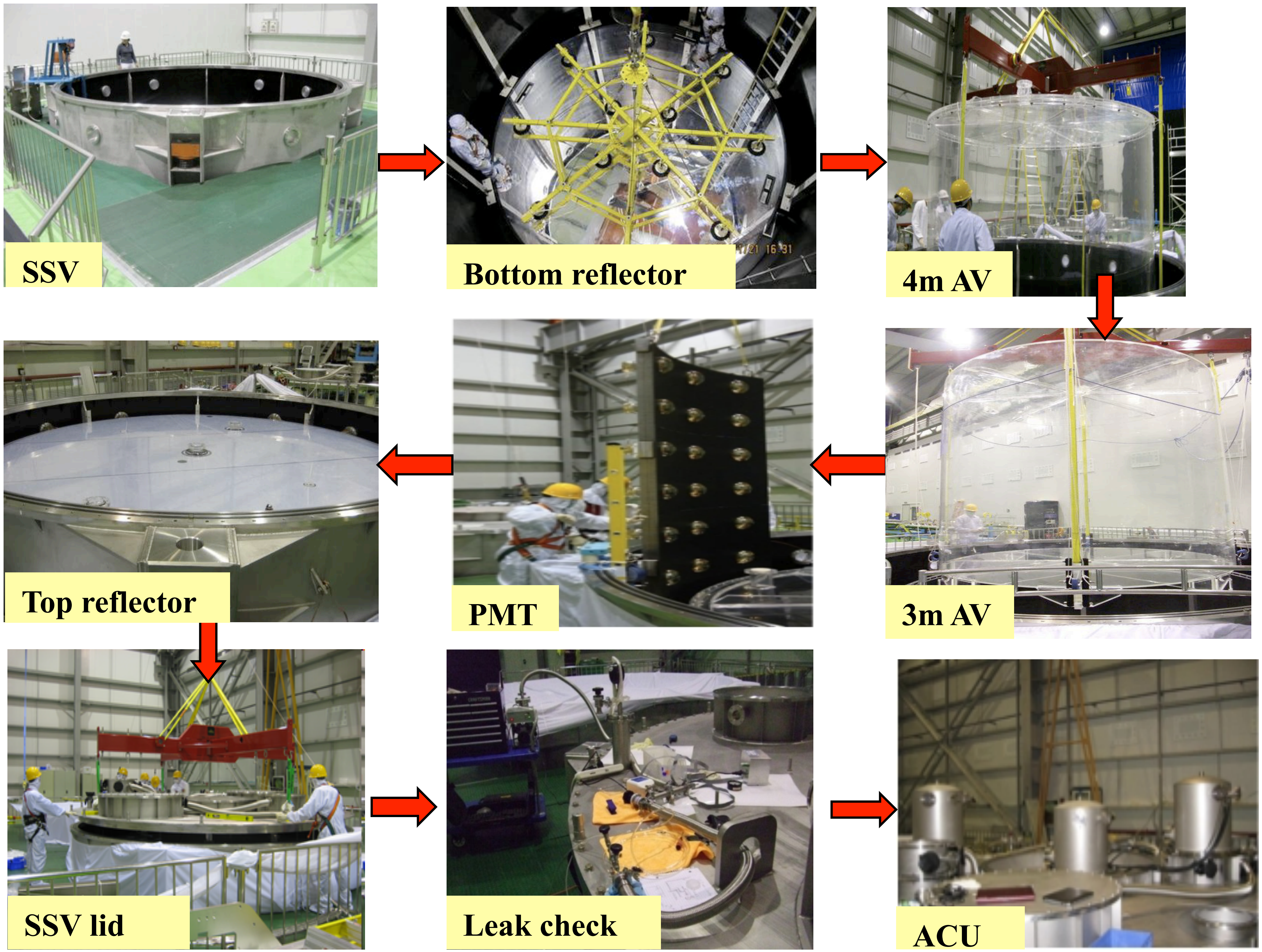
- 8-inch PMTs mounted on frames, 288 @Near, 384 @Far



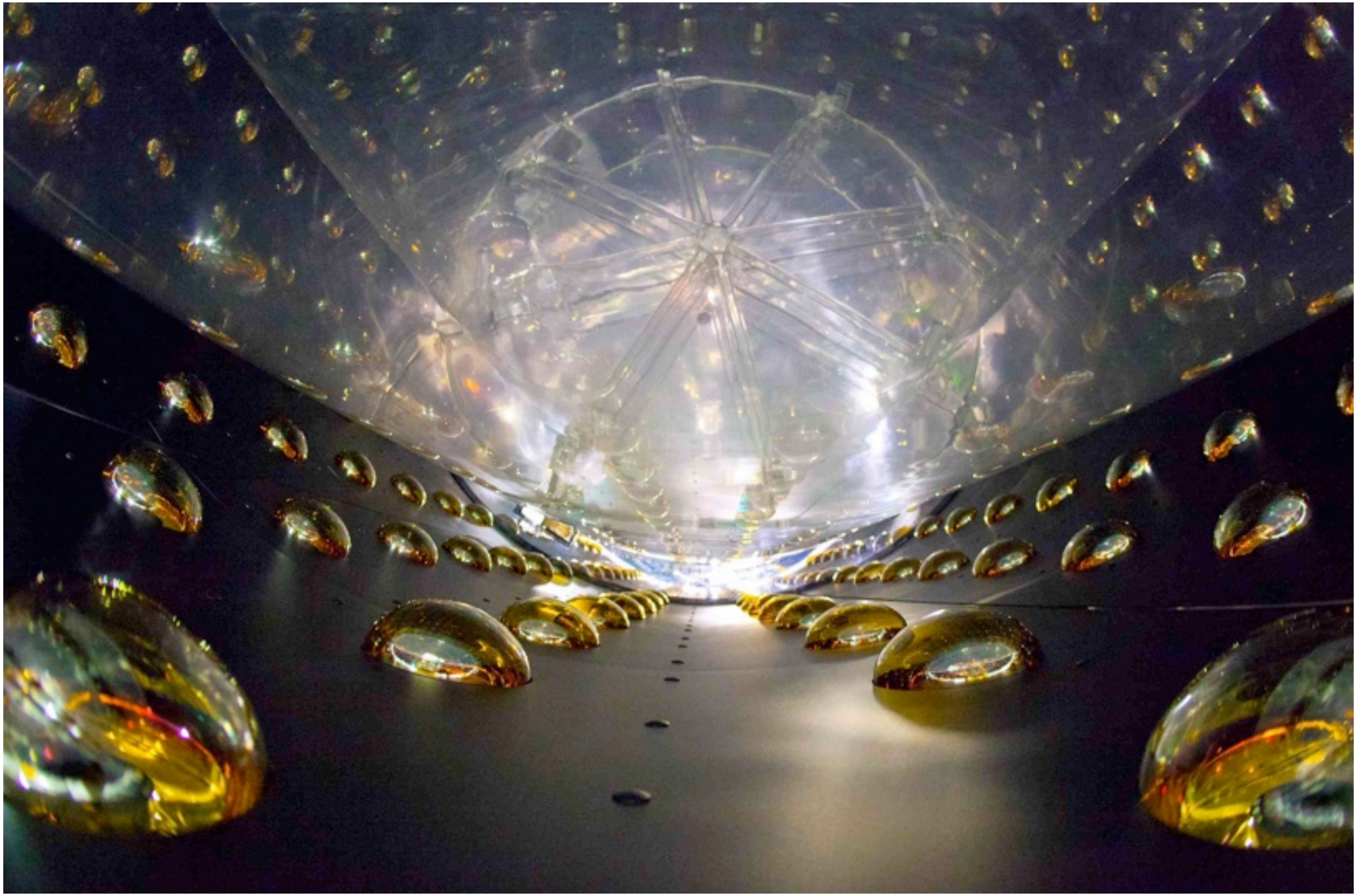
Resistive Plate Chamber (RPC)

- Independent muon tagging
- Retractable roof above pool
- 54 modules @Near, 81 @Far

Antineutrino Detector Assembly



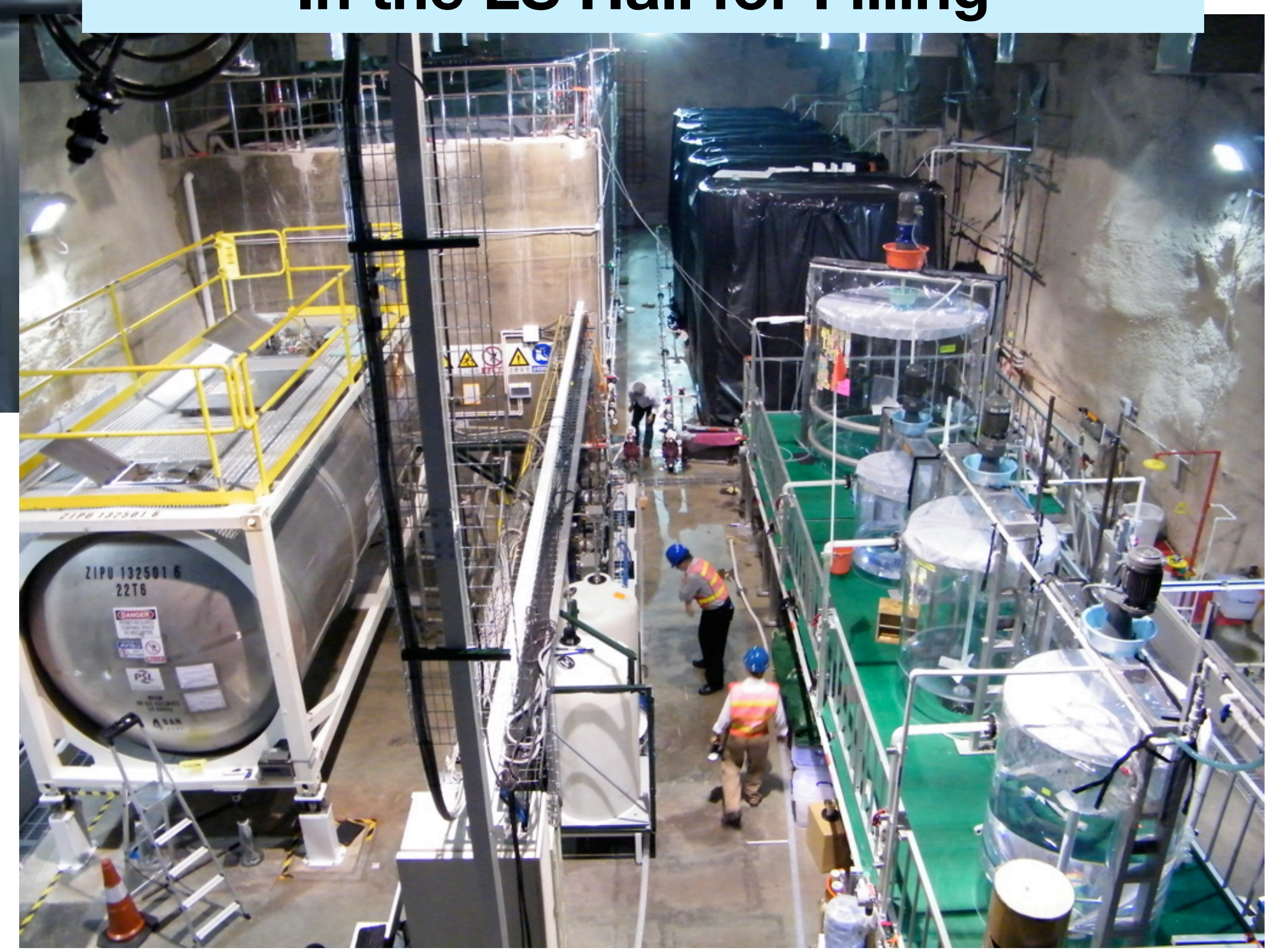
Interior of Antineutrino Detector



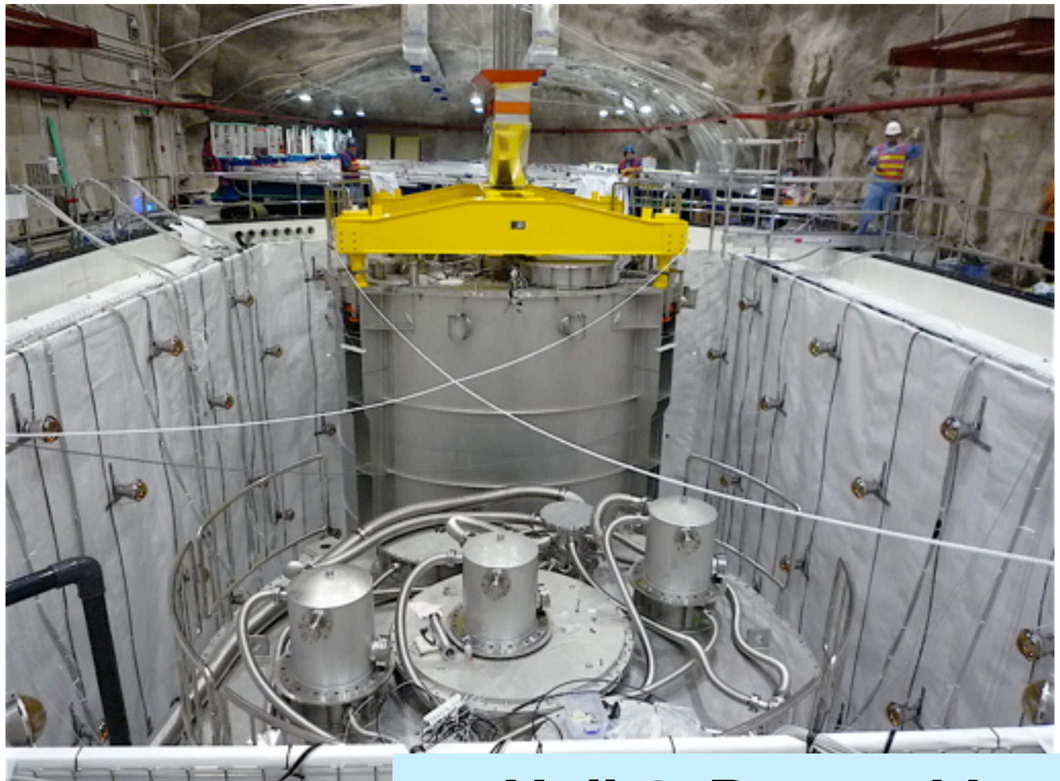
Detector Transporting

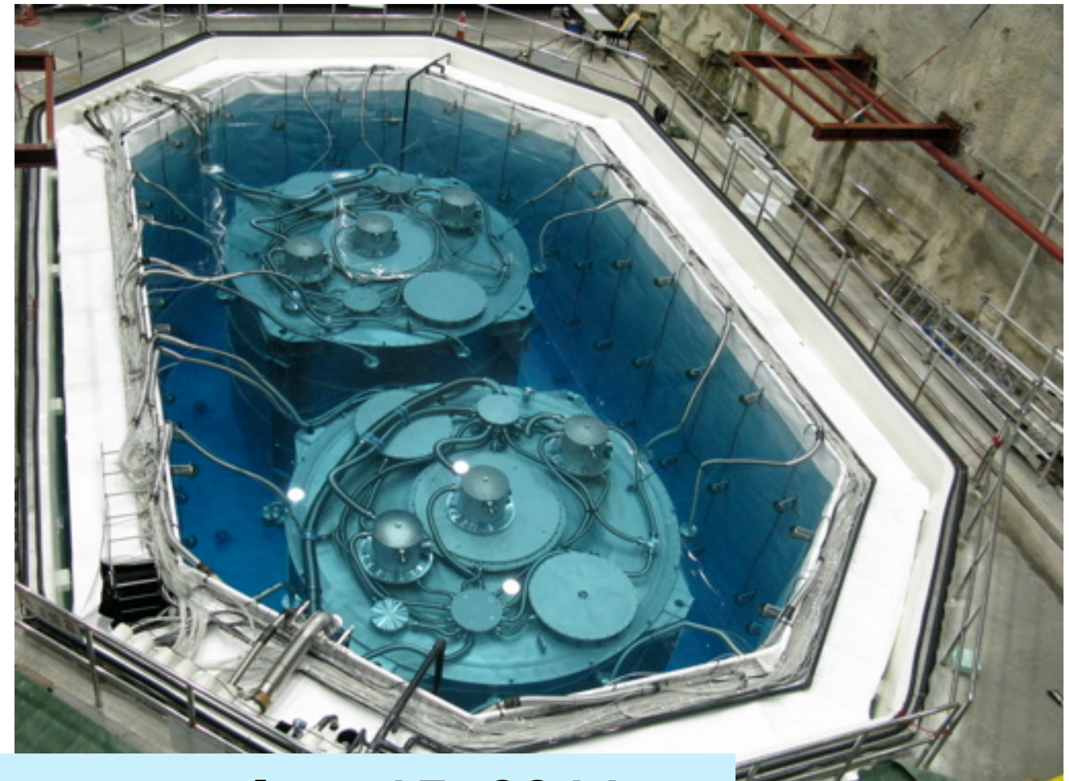
Move detector into the tunnel

In the LS Hall for Filling

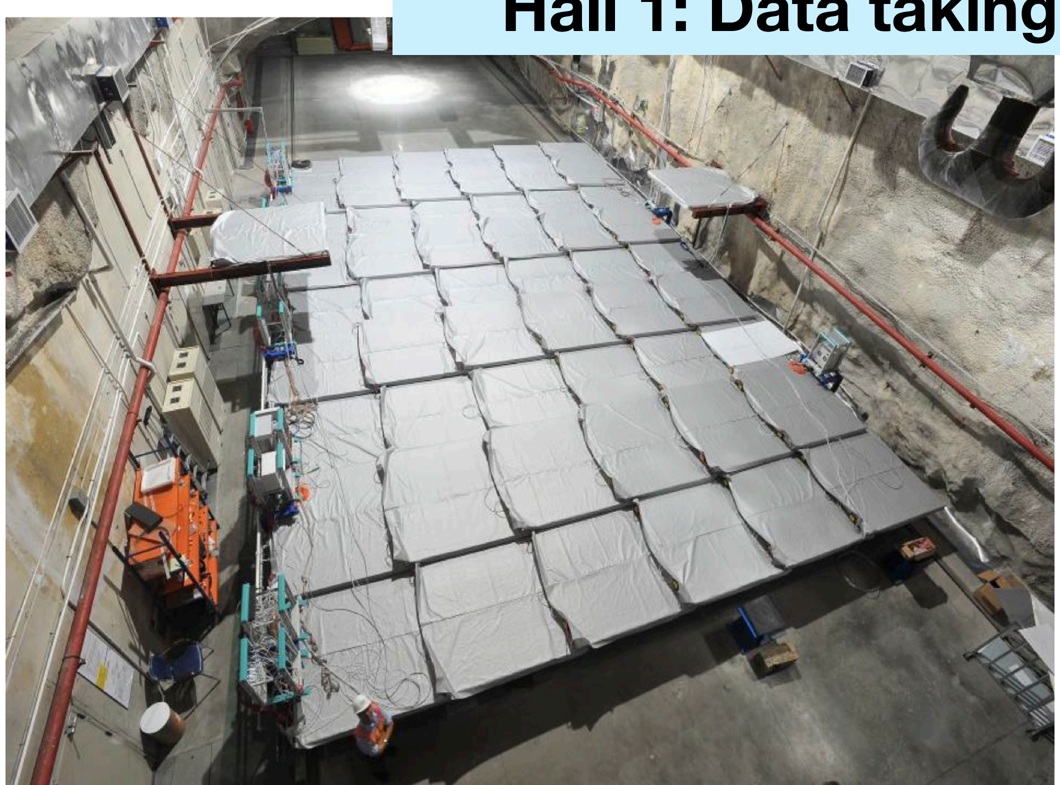


Hall 1: Completed



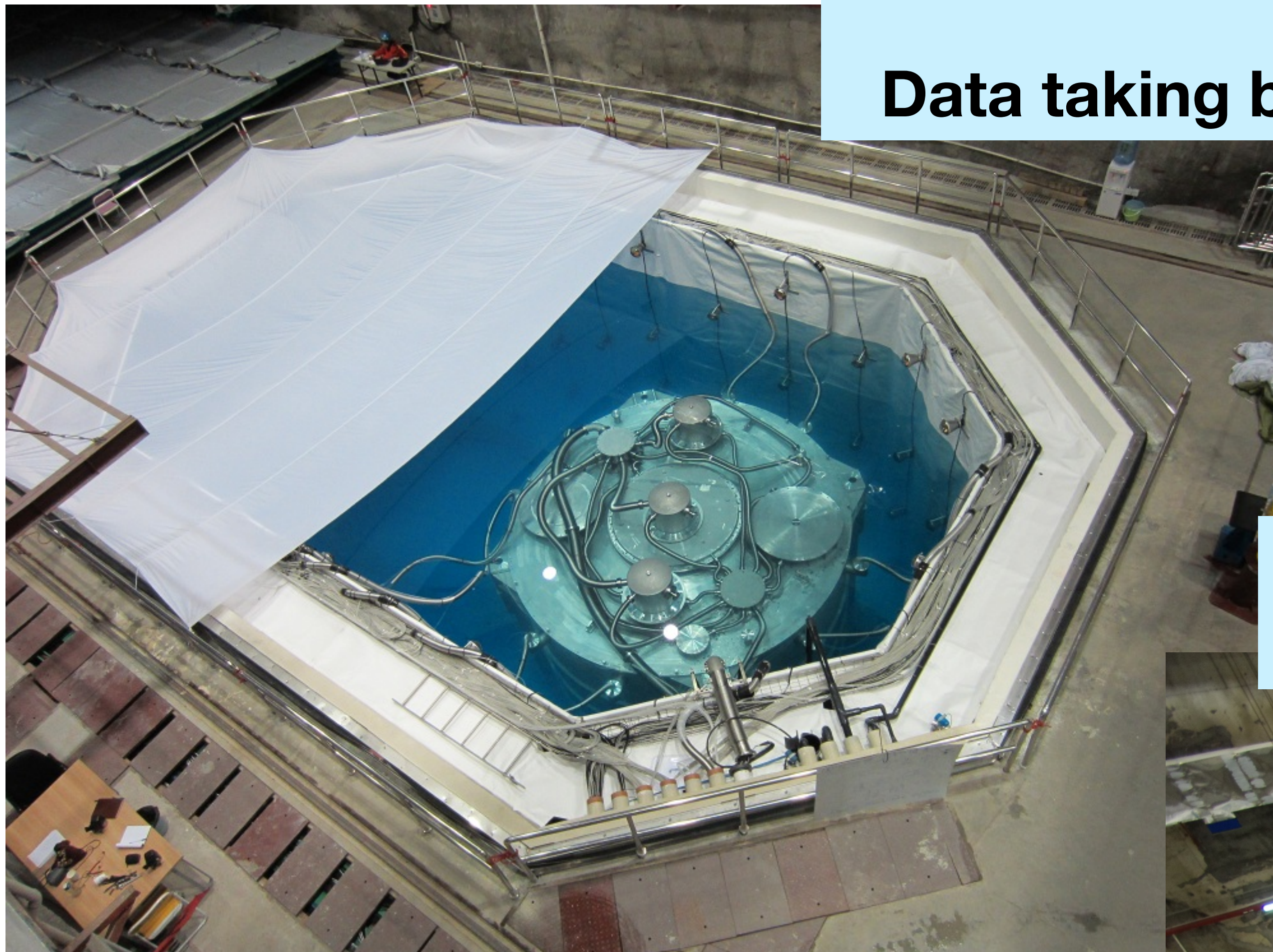


Hall 1: Data taking began on Aug 15, 2011

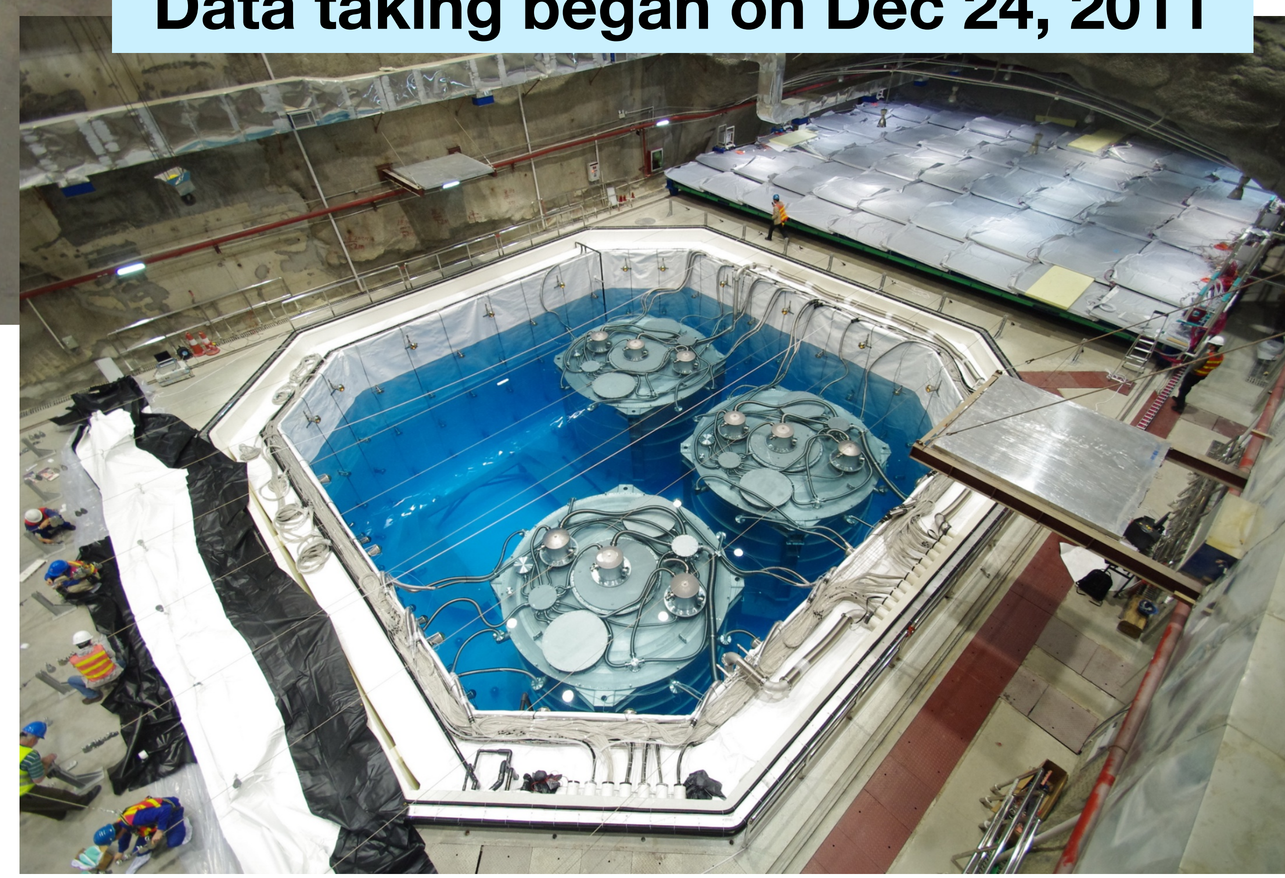


Hall 2 and Hall 3

Hall 2
Data taking began on Nov 5, 2011

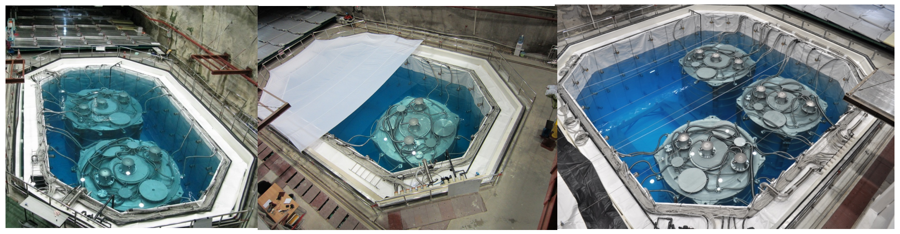


Hall 3
Data taking began on Dec 24, 2011



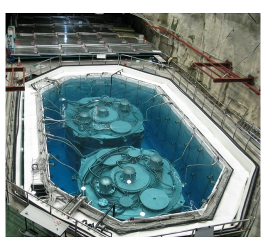
Two more ADs still in assembly.
Installation planned for Summer 2012

Data Period



Current Oscillation Analysis

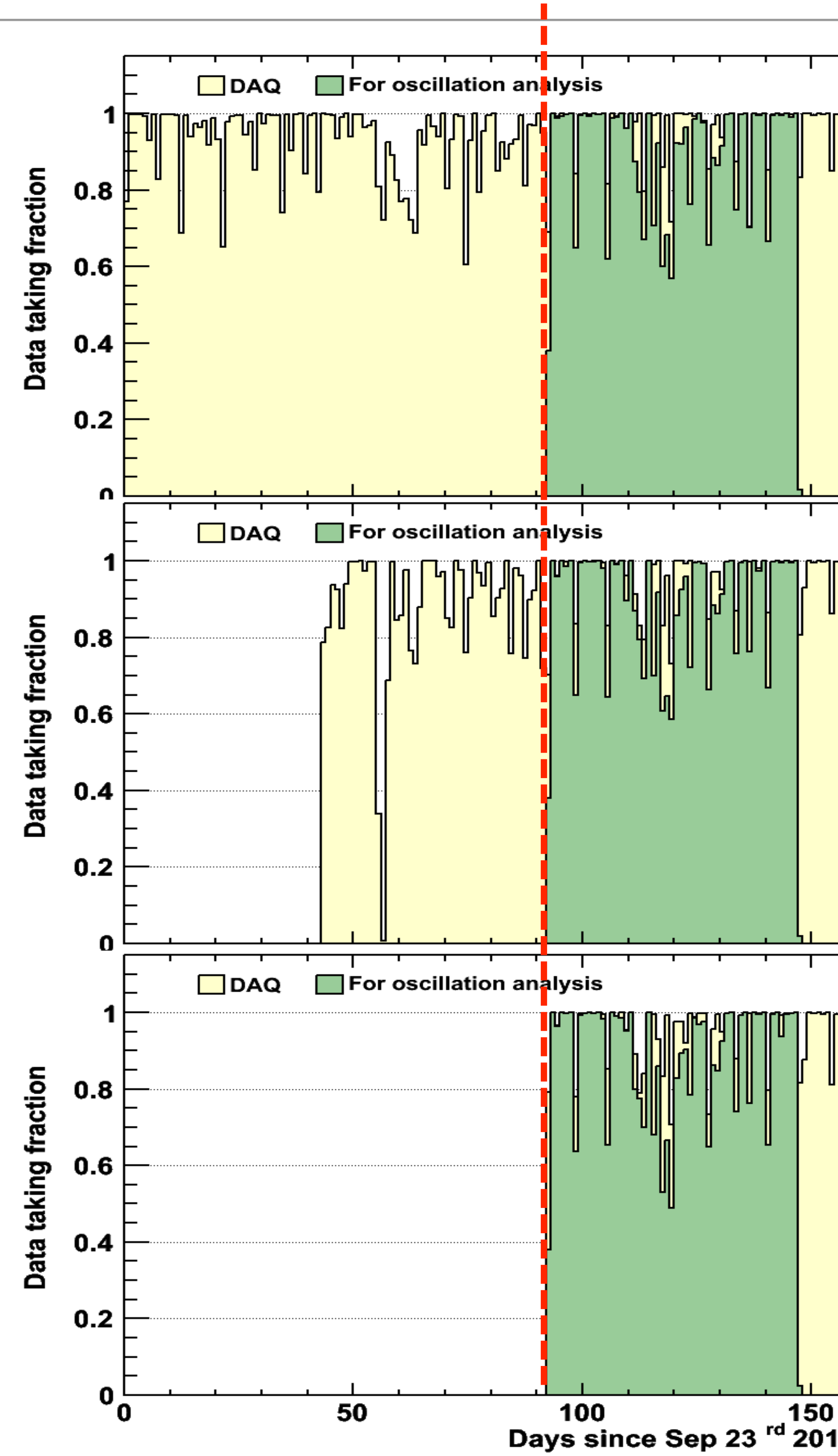
- Dec 24, 2011 - Feb 17, 2012
- All 3 halls (6 ADs) operating
- Data Acquisition (DAQ) uptime > 97%
- Analysis data: ~89% (~50 live-days)



Two Detector Analysis

- Sep 23, 2011 - Dec 23, 2012
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.

arXiv: 1202:6181 (2012), submitted to NIM



Data Analysis

Blinded Information

- True Target Mass
- True baselines from detectors to reactors
- True reactor flux

$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E, L_{\mathrm{f}})}{P_{\mathrm{sur}}(E, L_{\mathrm{n}})}\right]$$

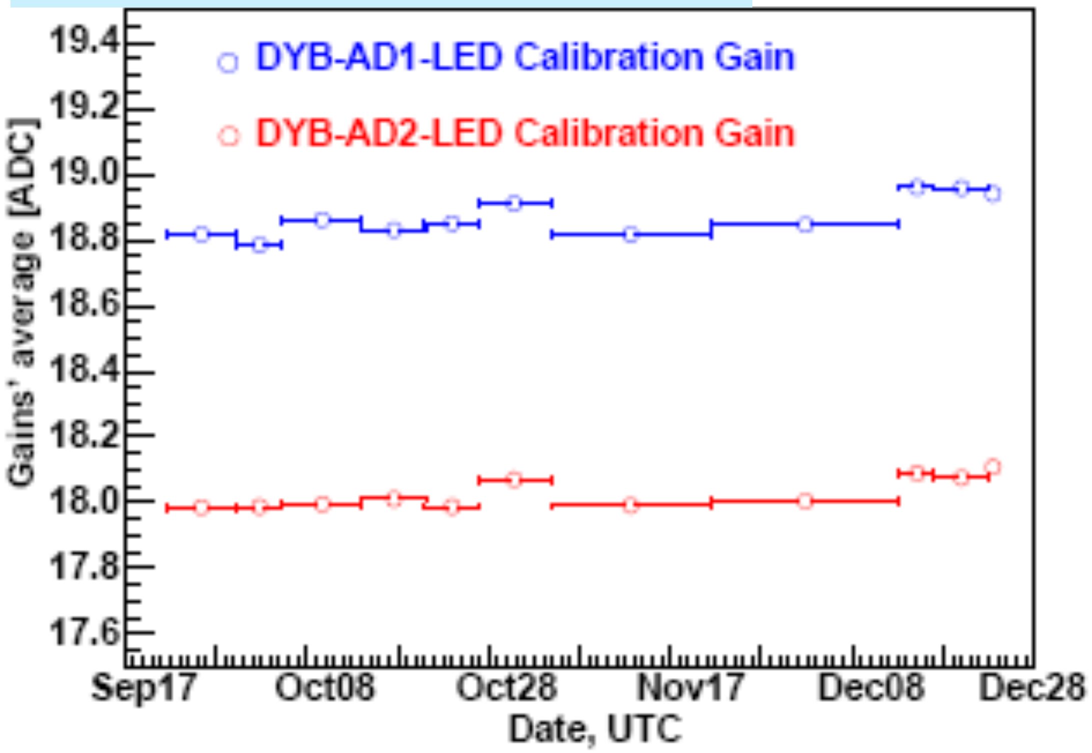
Multiple independent analyses to cross check results before unblinding

- Common data set
- Different
  - Energy Calibration / Reconstruction
  - Antineutrino Candidate Selection / Efficiency Estimation
  - Background Estimation
  - θ_{13} Rate Analysis

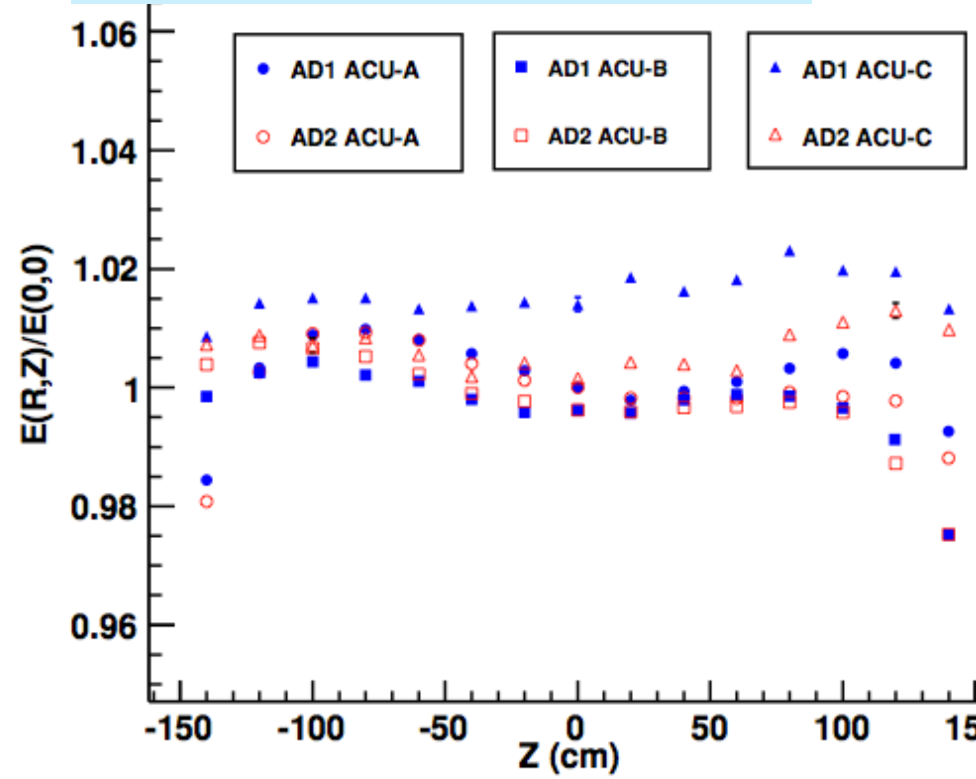
Only results from one analysis are presented here

Calibration

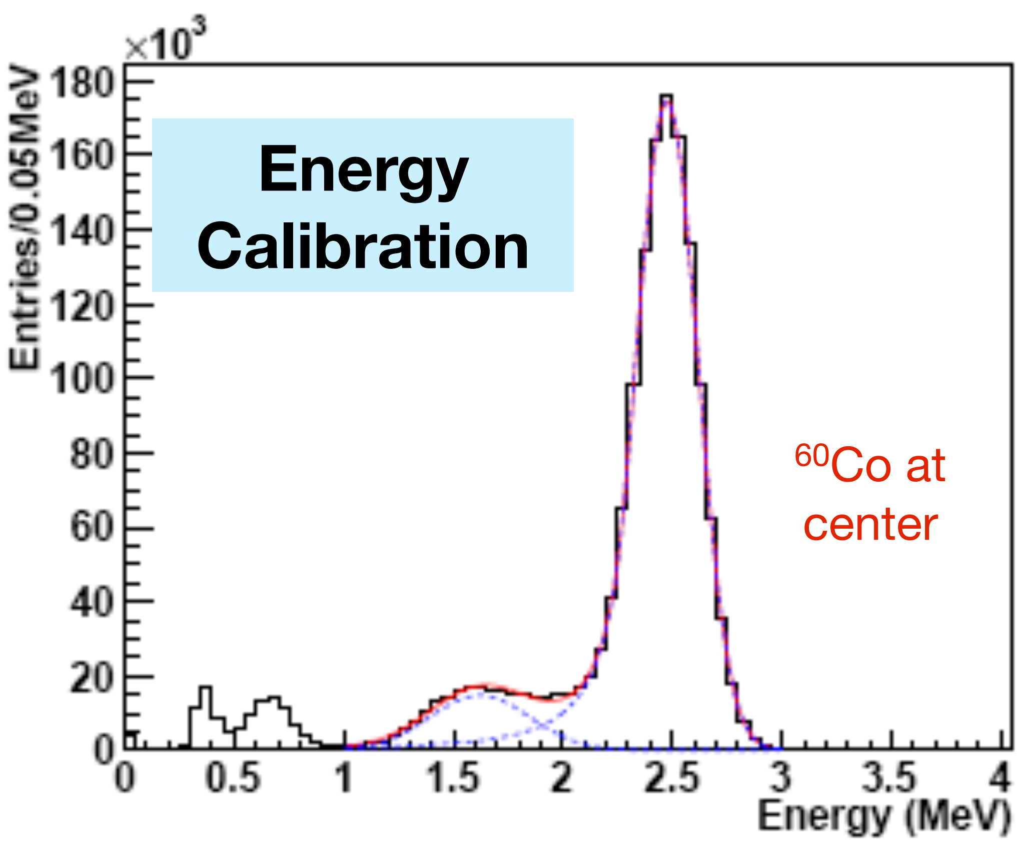
PMT Gain vs. Time



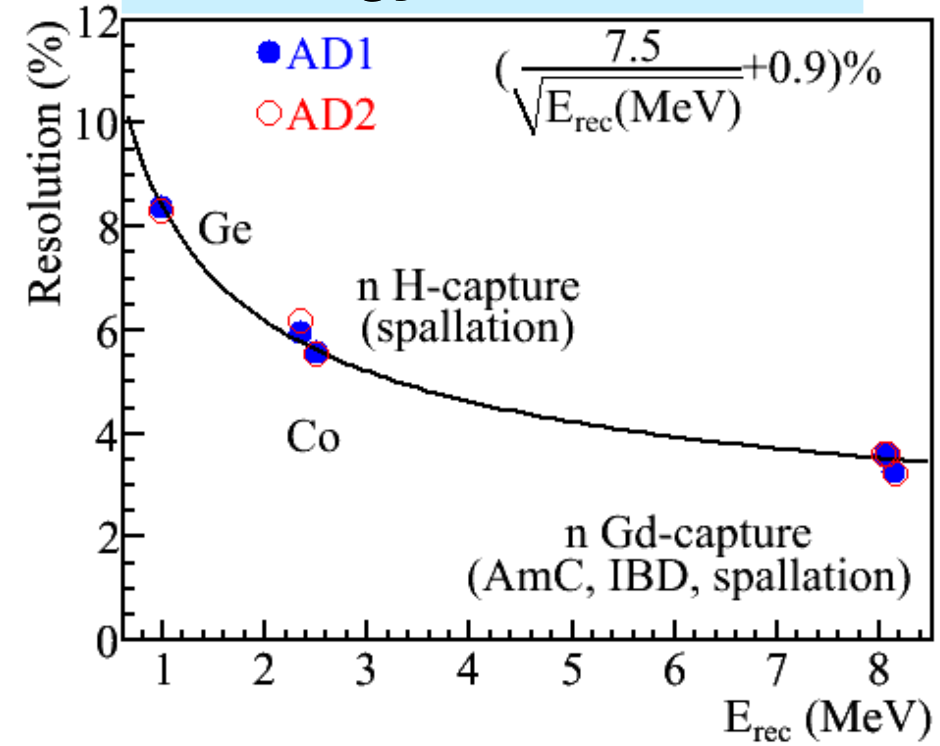
Energy vs. Position



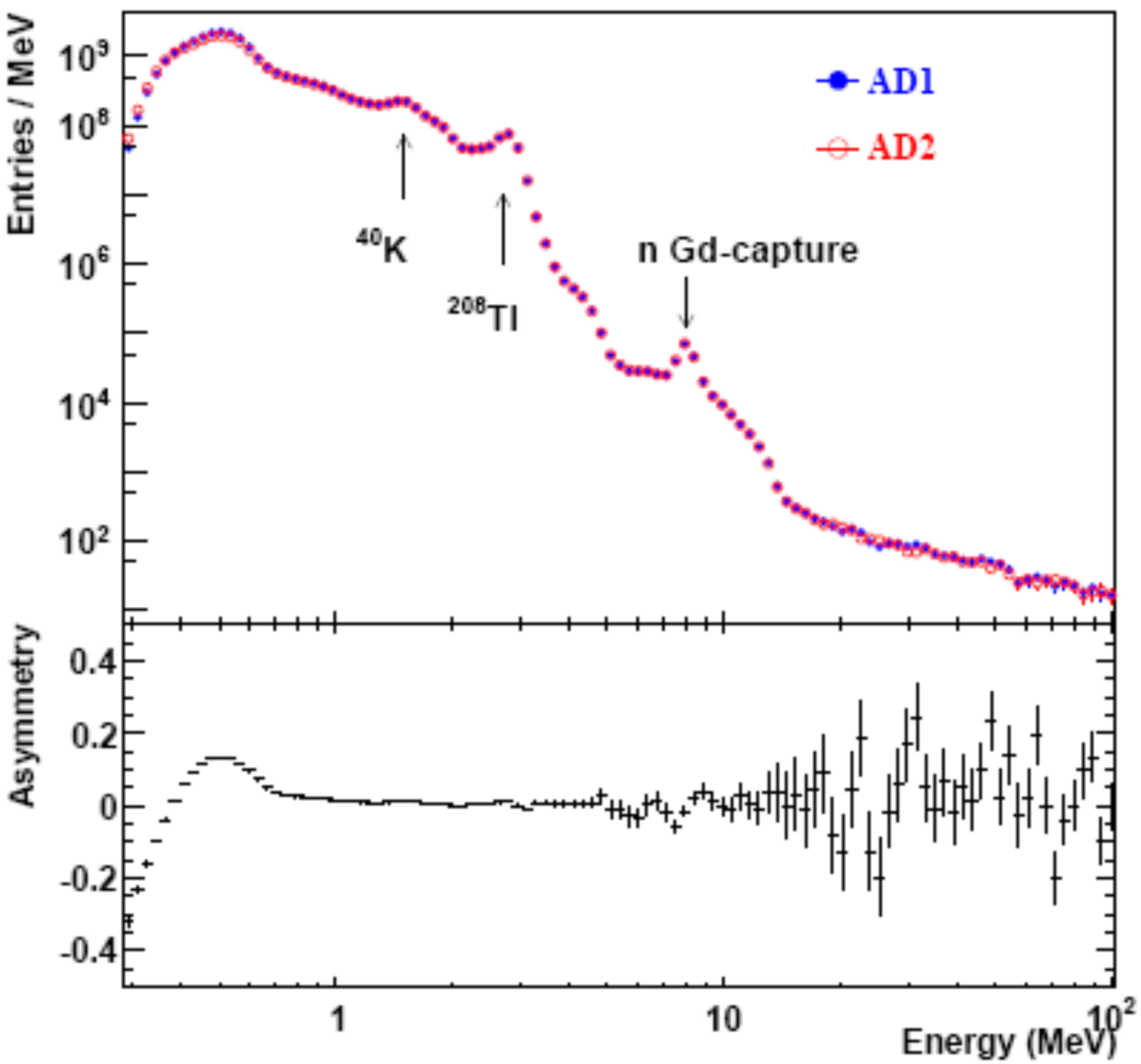
Energy Calibration



Energy Resolution



Energy Spectrum of All Events



- After applying muon veto, ~65 Hz > 0.7 MeV in each detector
- Dominated by low energy radioactivity from U/Th/Radon chain and K40
  - external: stainless steel, PMTs
  - internal: scintillator liquid

Task: Select anti-neutrinos out of these.
(~800 events/AD/day @Near, ~80 events/AD/day @Far)

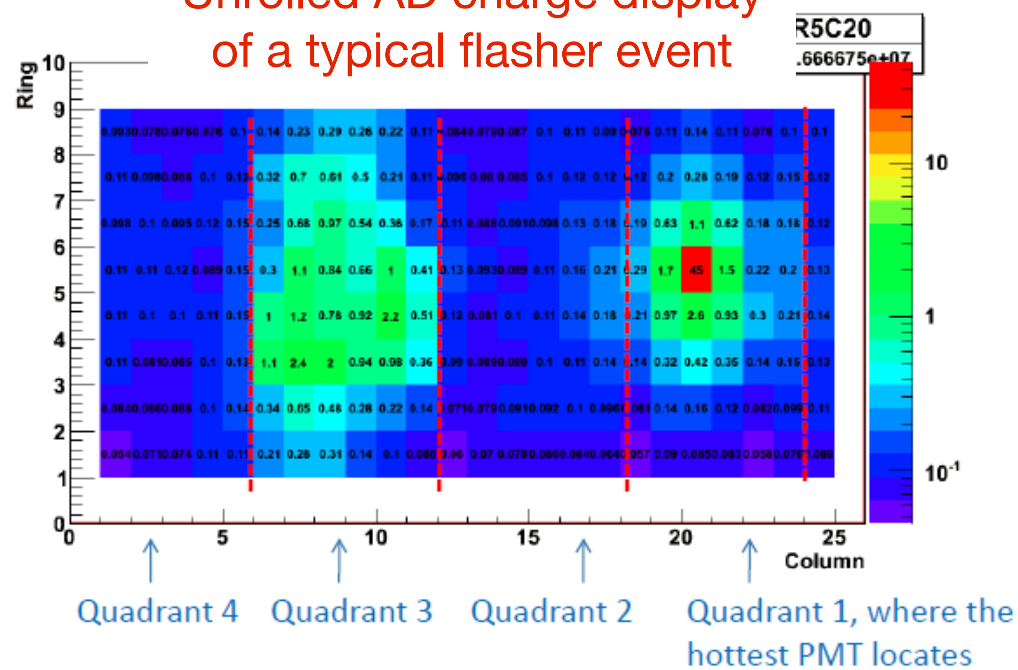
Anti-neutrino (IBD) Selection

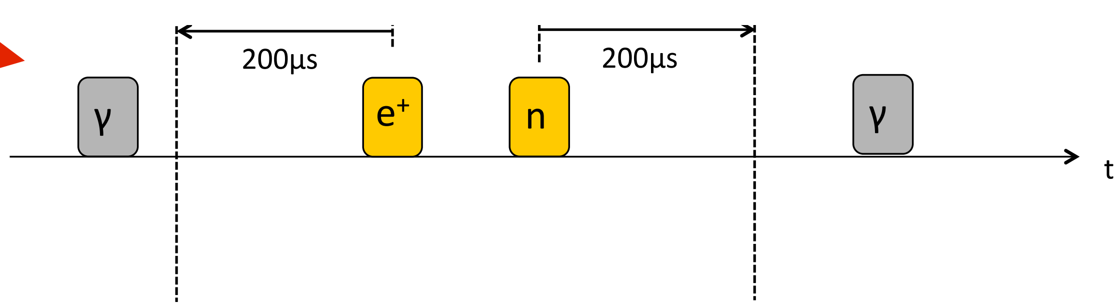
Use IBD prompt + delayed signal to select anti-neutrino candidates

Selection:

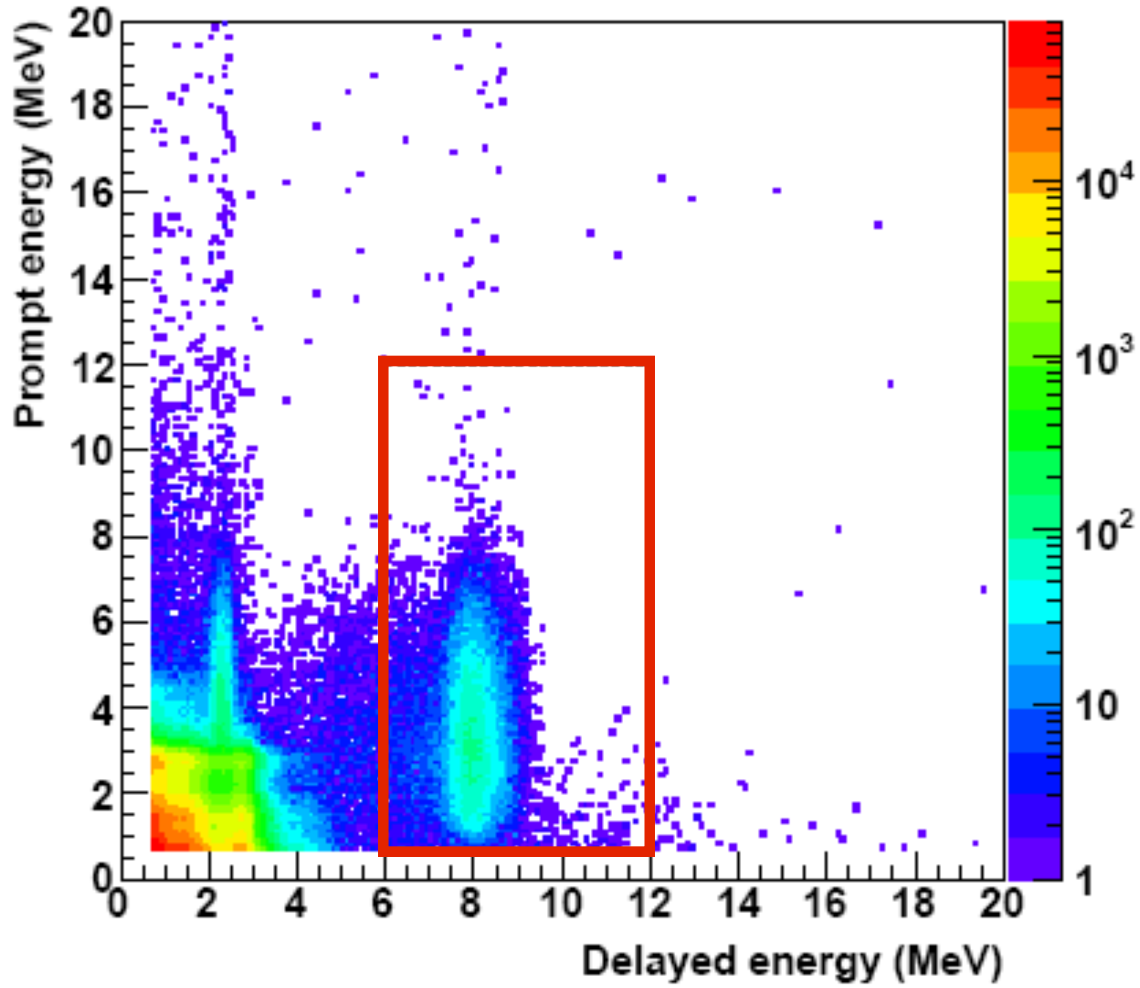
- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.

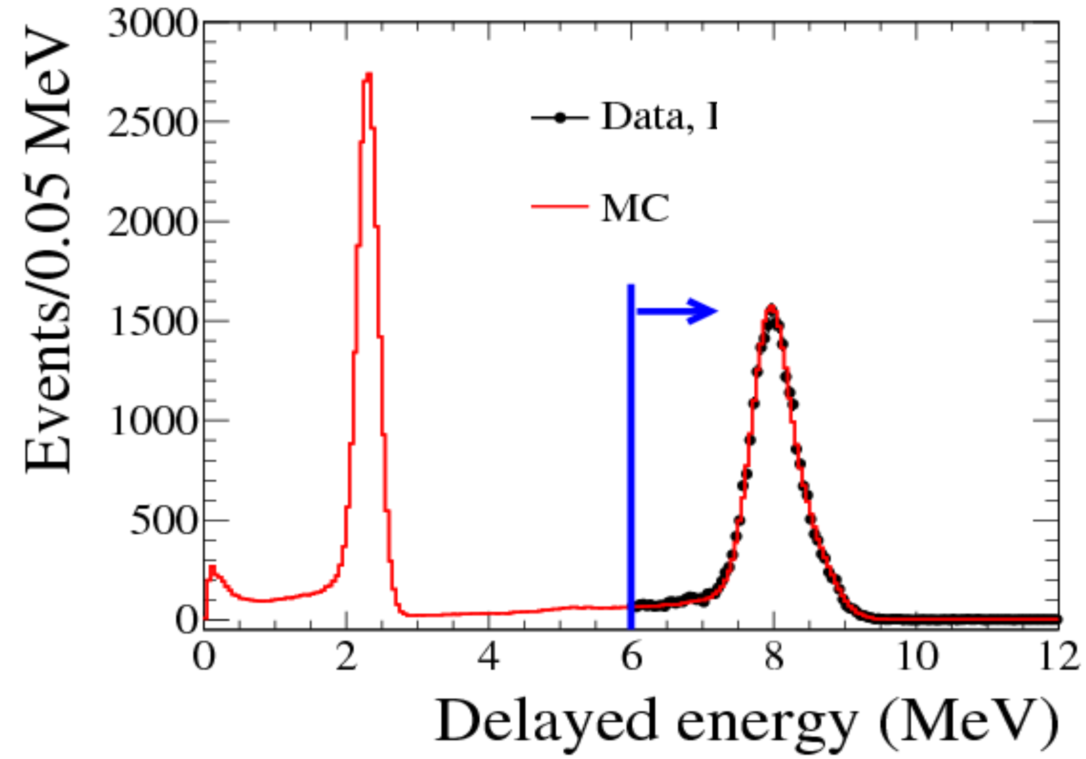
Unrolled AD charge display of a typical flasher event

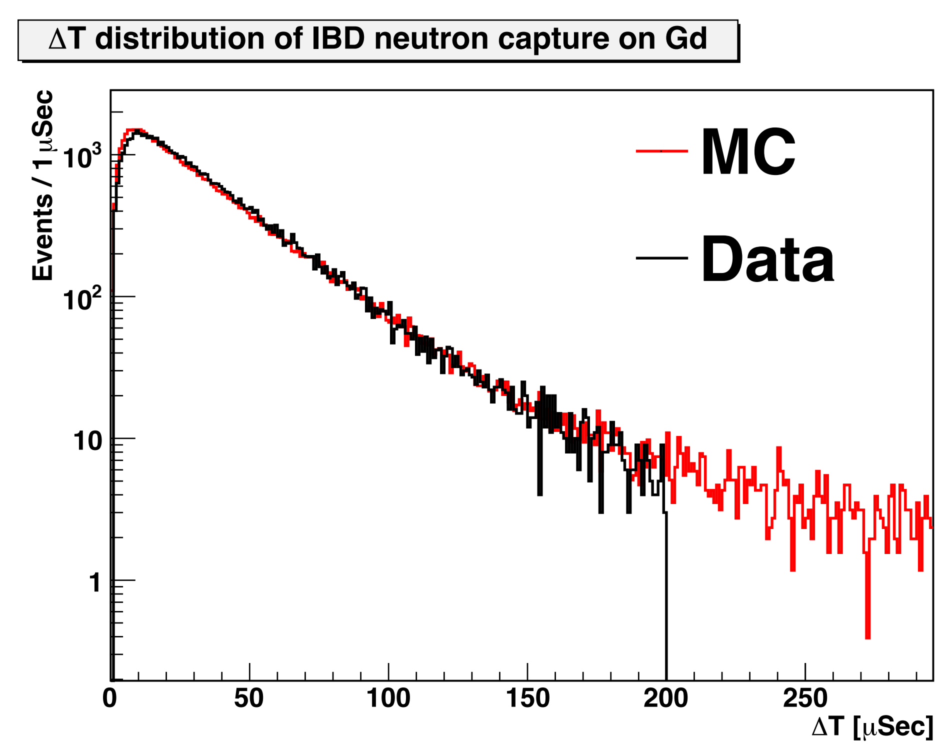




Antineutrino Candidate Distribution







clear separation of anti-neutrino signals from most other events

Remaining Background

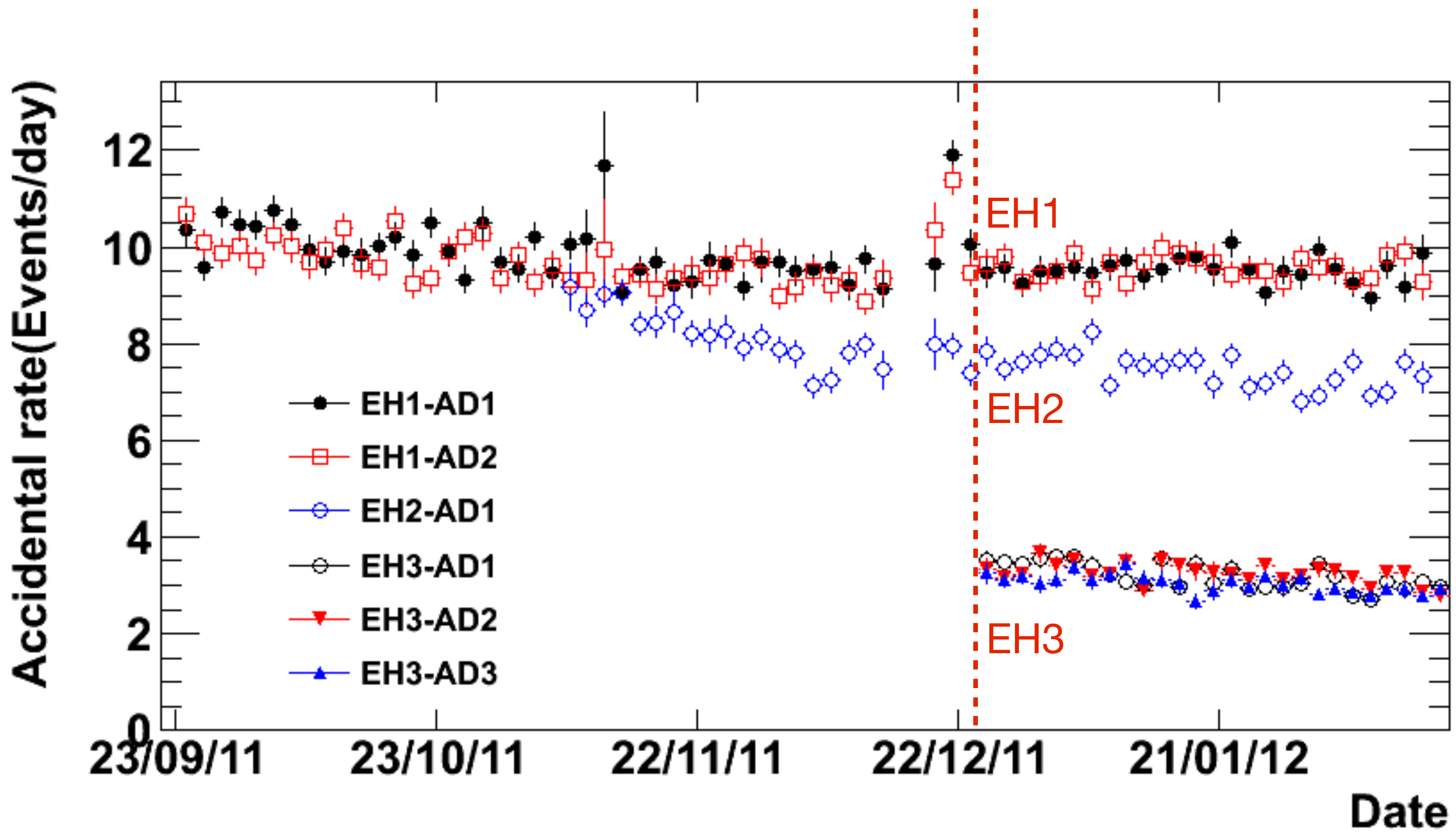
(B/S = background/signal @Far)

- Uncorrelated
  - Accidentals: Two uncorrelated events ‘accidentally’ passing the cuts and mimic IBD event. (B/S: 4.5%)
- Correlated
  - Muon spallation:
    - $^{9}Li/^{8}He$ (B/S: 0.2%)
    - Fast Neutron (B/S: 0.06%)
  - Correlated Signals from $^{241}Am^{13}C$ Source (B/S 0.3%)
  - $^{13}C(\alpha, n)^{16}O$ (B/S 0.04%)

Total B/S ratio is ~5% at Far site, ~2% at Near site

Background: Accidentals

Two uncorrelated events mimic the anti-neutrino (IBD) signals



Rate and spectra can be accurately predicted from the singles data

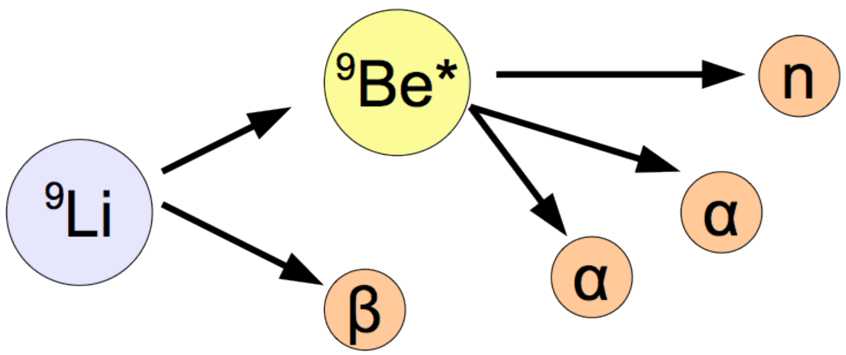
Most delayed-like single events are from beta-decays of long-live muon spallation isotopes

B/S ratio is ~4.5% at Far site, ~1.4% at Near site

Background: Muon Spallation

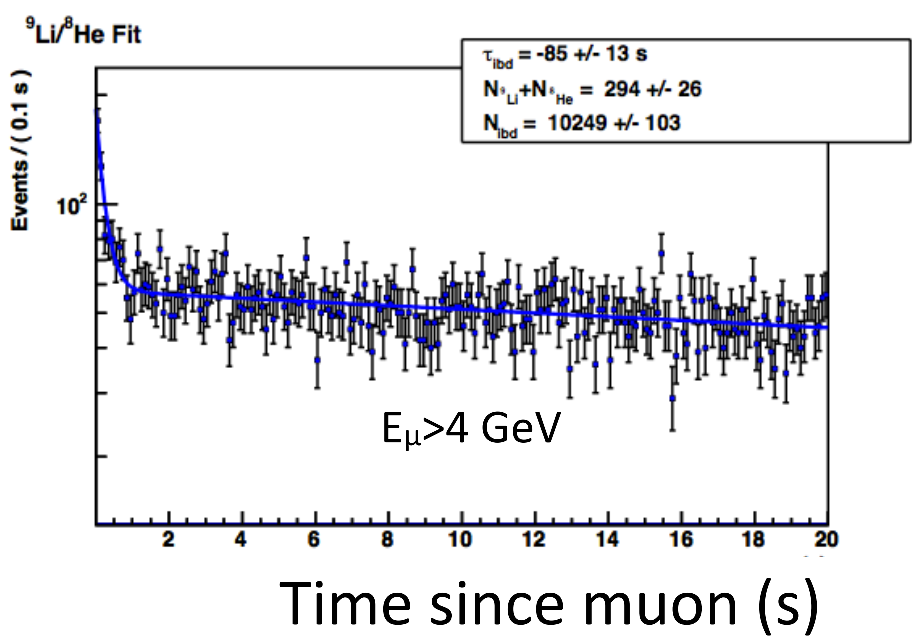
β-n decay:

- Prompt: β-decay
- Delayed: neutron capture



^{9}Li: $\tau_{1/2} = 178$ ms, Q = 13. 6 MeV

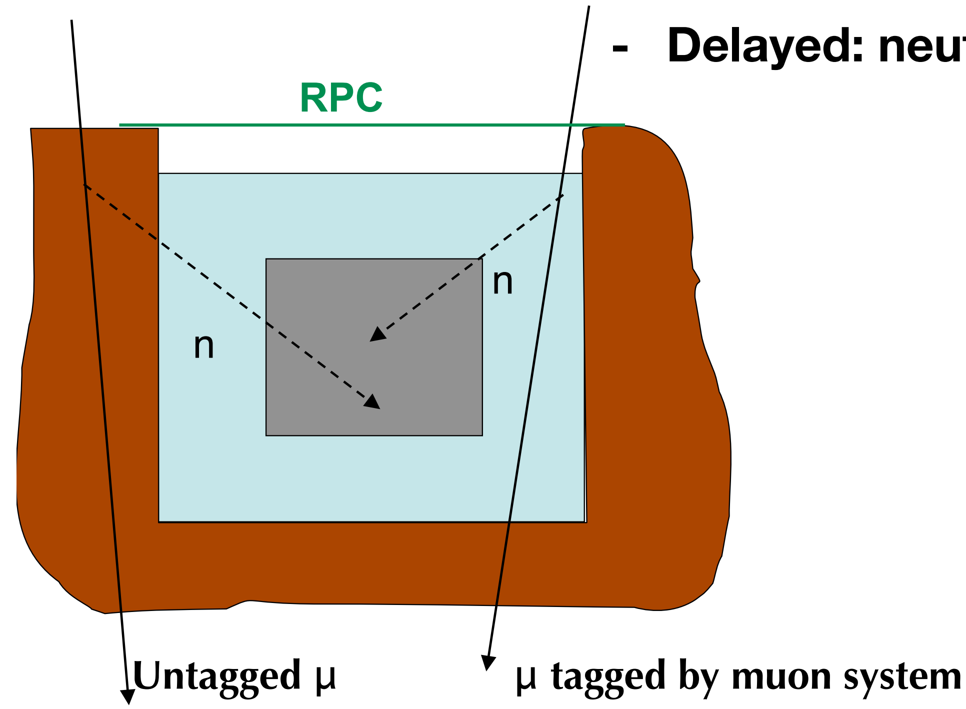
^{8}He: $\tau_{1/2} = 119$ ms, Q = 10.6 MeV

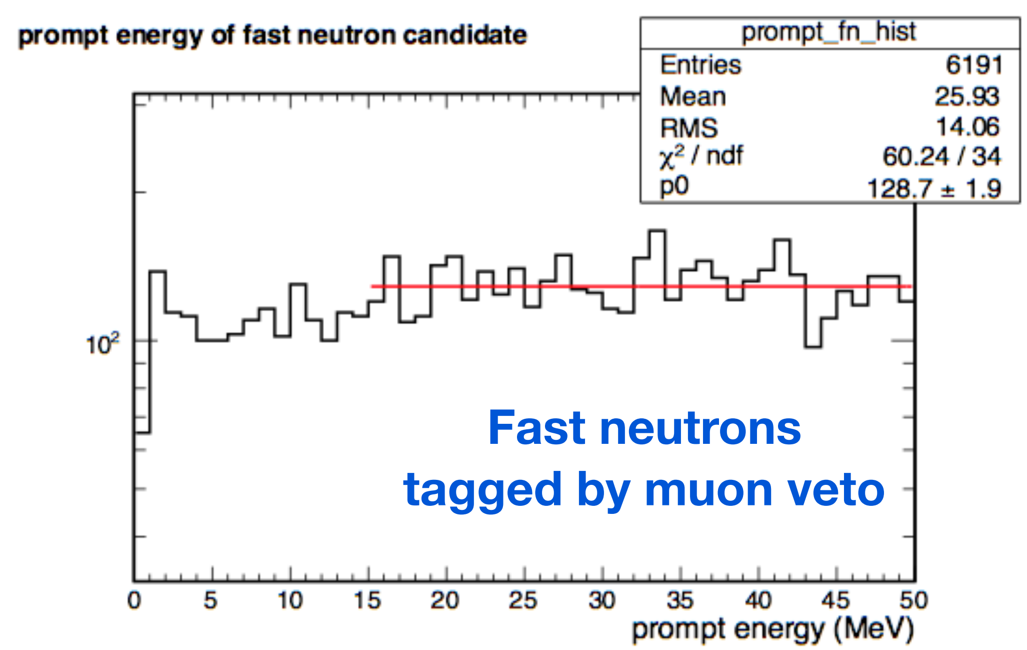


B/S: 0.2%

Fast neutron

- **Prompt: proton recoil**
- **Delayed: neutron capture**



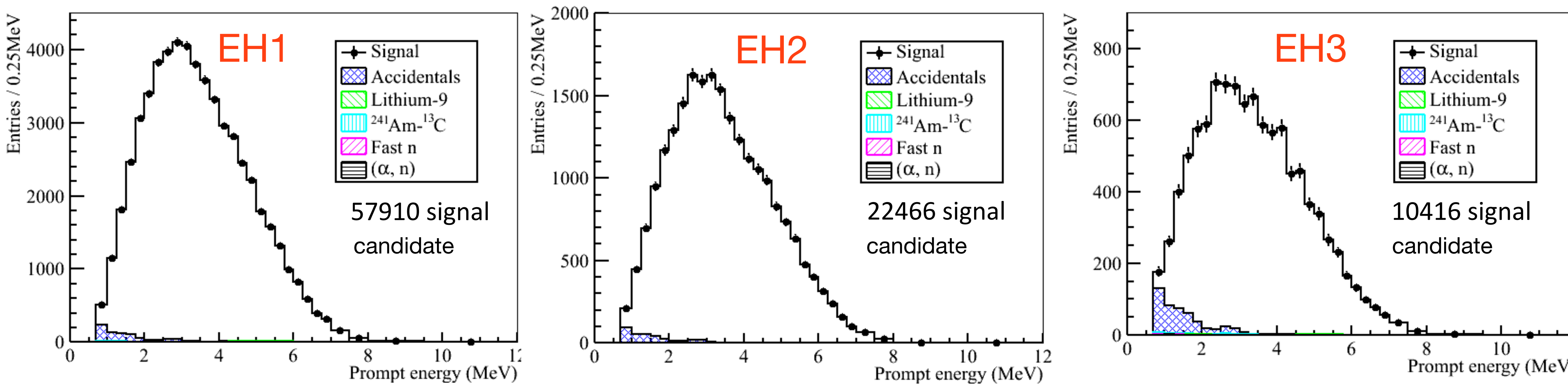


B/S: 0.06%

Data Set Summary

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	28935	28975	22466	3528	3436	3452
DAQ live time (days)	49.5530		49.4971	48.9473		
$\epsilon_\mu \cdot \epsilon_m$	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (per day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29 ±0.03	3.33 ± 0.03	3.12 ±0.03
Fast-neutron (per day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
^{9}Li/^{8}He (per AD per day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C correlated (per AD per day)	0.2±0.2					
^{13}C$(\alpha, n)^{16}$O background (per day)	0.04±0.02	0.04±0.02	0.035±0.02	0.03±0.02	0.03±0.02	0.03±0.02
IBD rate (per day)	714.17±4.58	717.86± 4.60	532.29±3.82	71.78 ± 1.29	69.80±1.28	70.39±1.28

High statistics anti-neutrino spectra



Summary of Systematics Uncertainties

	Detector		
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	0.01%
Combined	78.8%	1.9%	0.2%

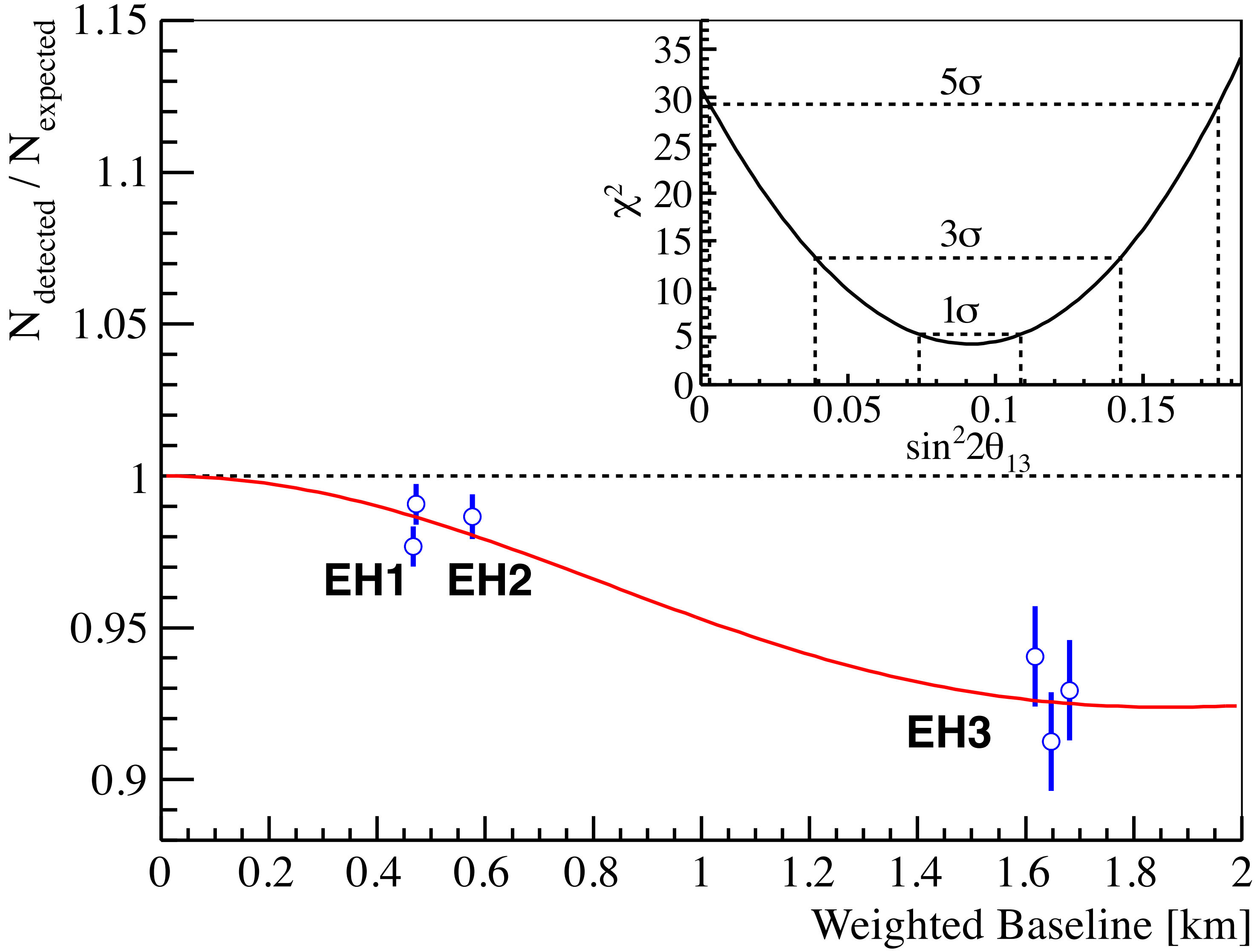
In far/near oscillation analysis, only detector uncorrelated uncertainties are meaningful

Total detector systematics are smaller than the far site statistics (1%)

Influence of reactor relative core-to-core uncertainty (0.8%) translated into 0.04% detector uncorrelated systematics by far/near measurement (reduction by a factor of 20)

Rate Analysis Result

Estimate θ_{13} using measured rates in each detector



- Clear deficit at far site is observed, far/near ratio is measured to be

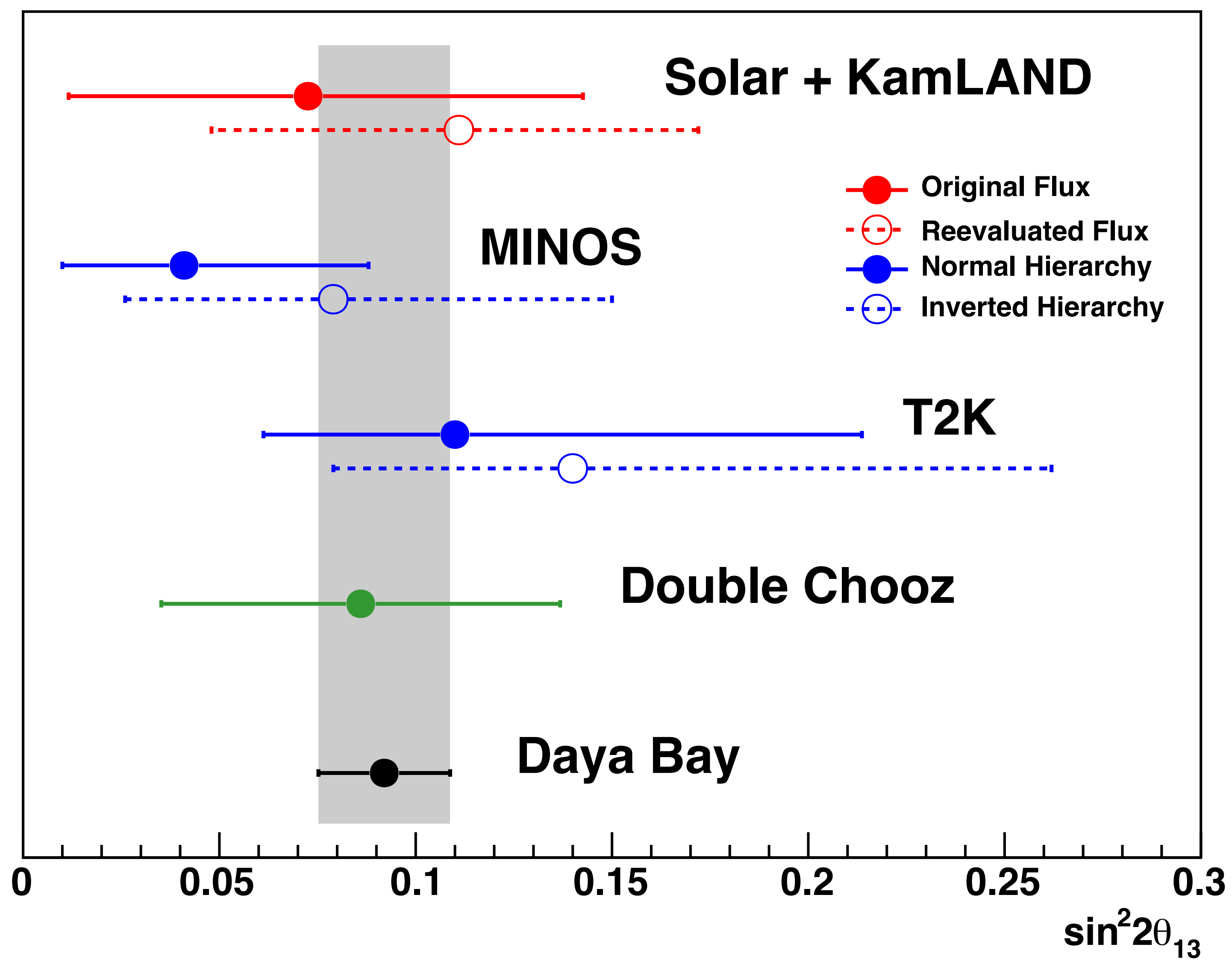
R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

- Use standard χ^2 approach to estimate θ_{13}, without constraining the absolute rate (far vs. near relative measurement)

$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat) ± 0.005 (syst)

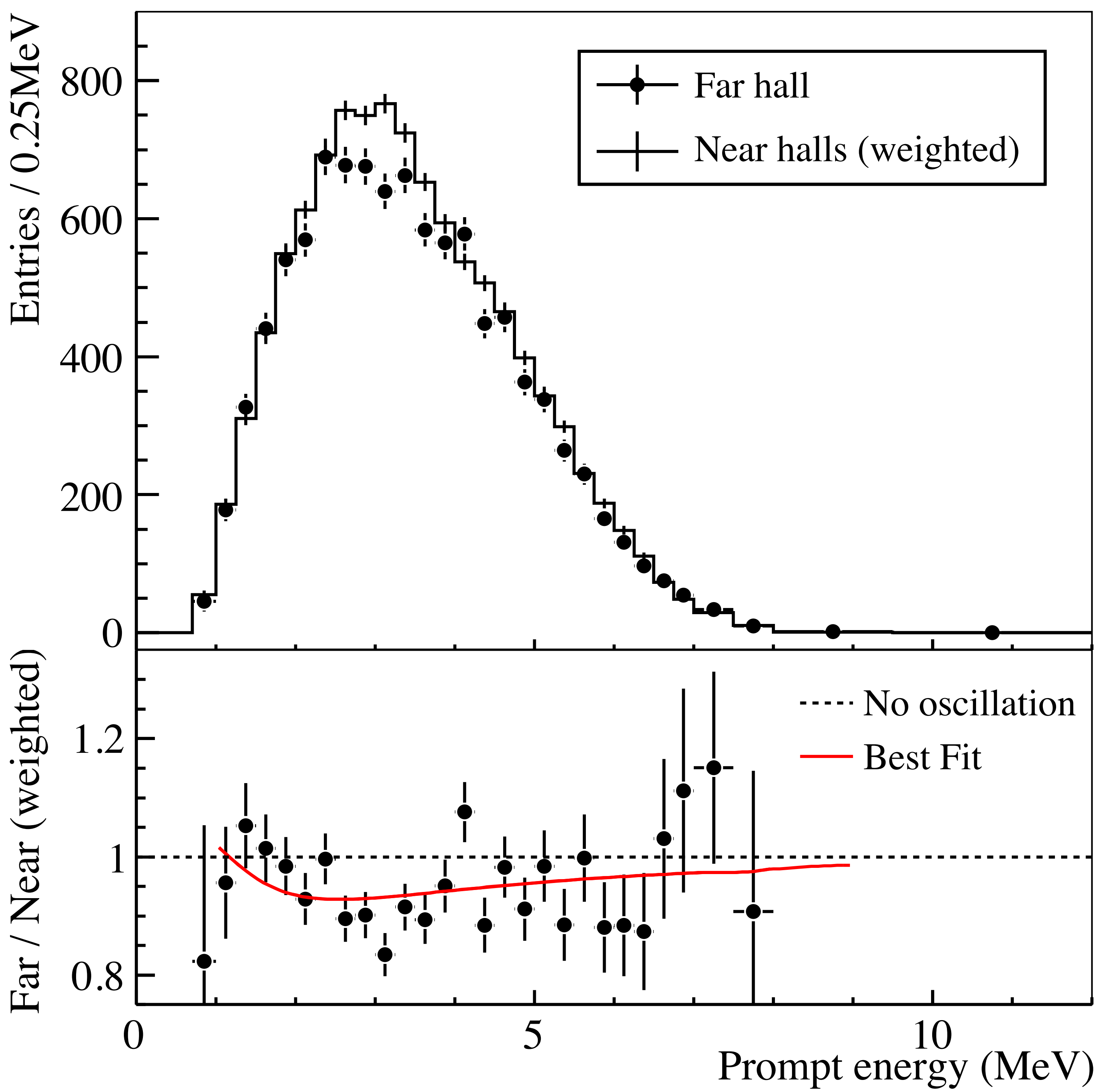
Theta13 Global

Daya Bay surpasses all existing estimates



Expect more statistics and improvements in analysis

Spectra Shape Analysis



- Current analysis is rate only, but spectra shape distortion is consistent with oscillation predication.
- With improved statistics and understanding of the energy scale systematics, will be able to have definite answer to the shape distortion.

Summary

- The Daya Bay reactor neutrino experiment has made an unambiguous observation of reactor electron antineutrino disappearance at ~2km.
  The deficit is measured to be

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

- Interpretation of disappearance as neutrino oscillation yields

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\text{stat}) \pm 0.005\ (\text{syst})$$

  $\sin^2 2\theta_{13} = 0$ is excluded at 5.2 standard deviations.

- Install the final pair of antineutrino detectors in summer 2012.

“We have finally observed all three mixing angles, now the gateway is open to explore the remaining parameters of neutrino oscillation”

Backup

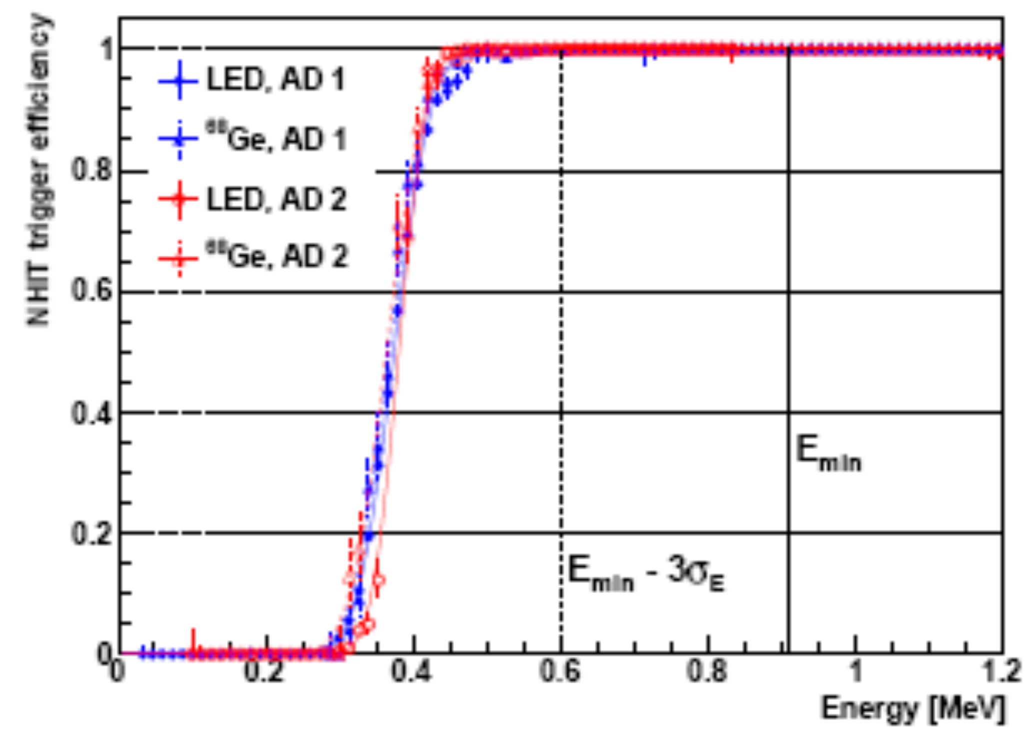
Trigger Performance

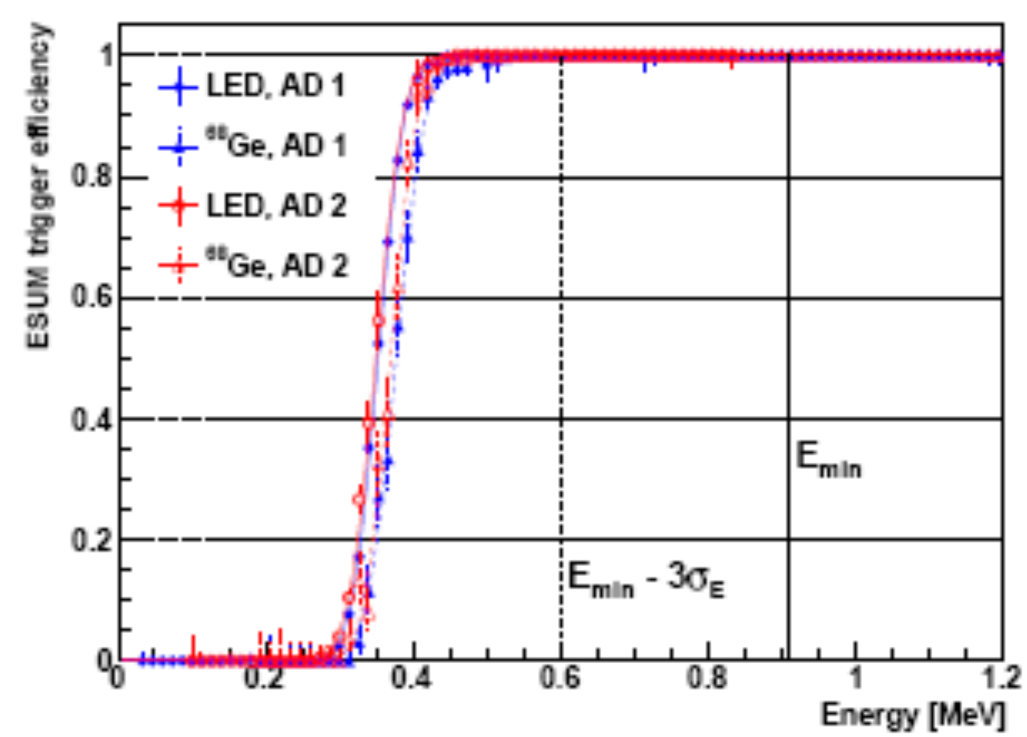
Trigger Thresholds:

- AD: >45 PMTs (digital trigger)
  >0.4 MeV (analog trigger)
- Inner Water Veto: > 6 PMTs
- Outer Water Veto: >7 PMTs
- RPC: ¾ layers in module

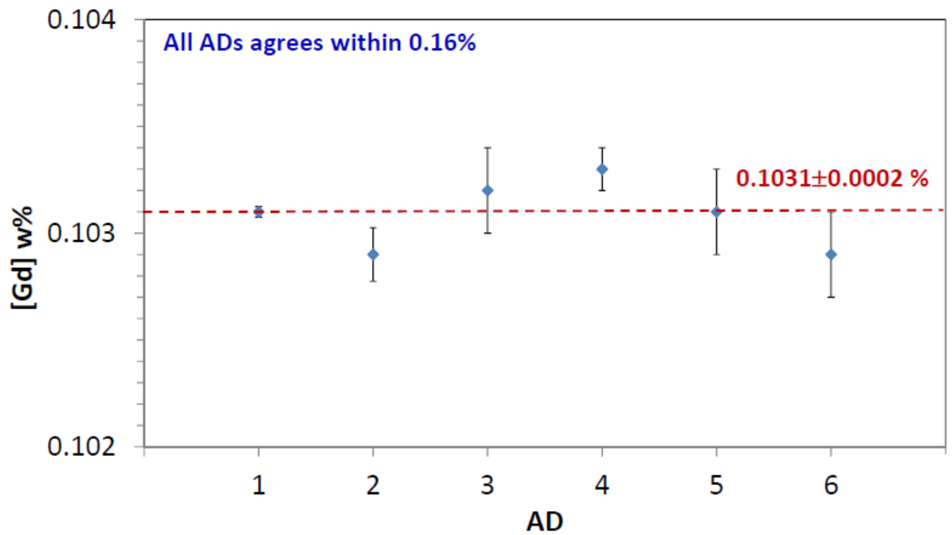
Trigger Efficiency:

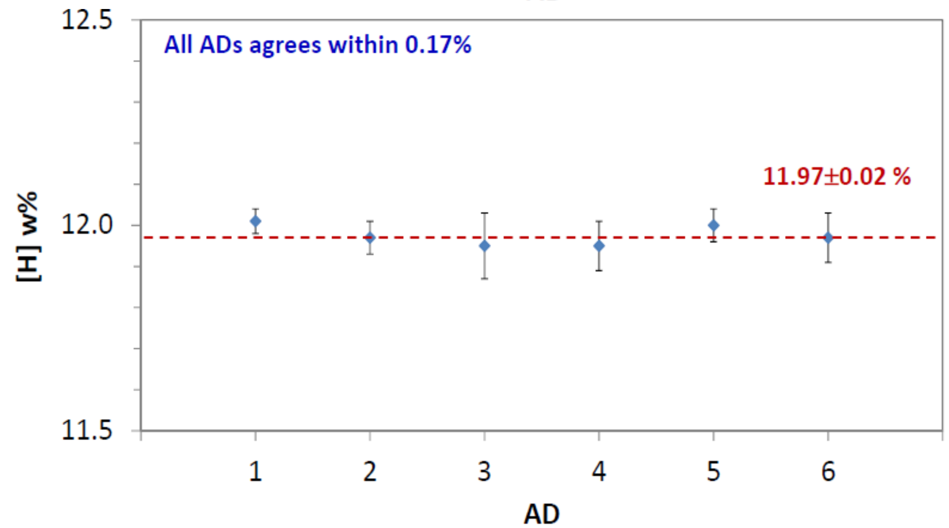
- No measureable inefficiency >0.7 MeV
- Minimum energy expected for prompt antineutrino signal is ~0.9 MeV.

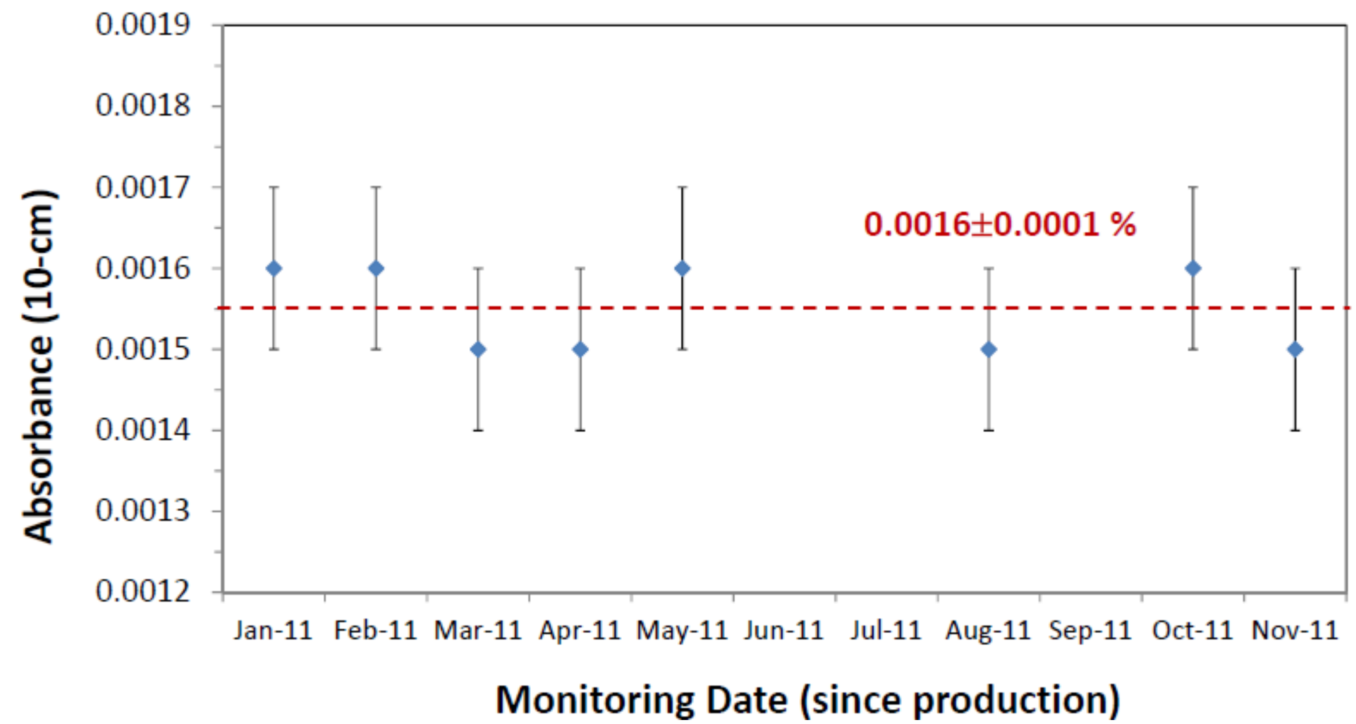




Scitillator Performance





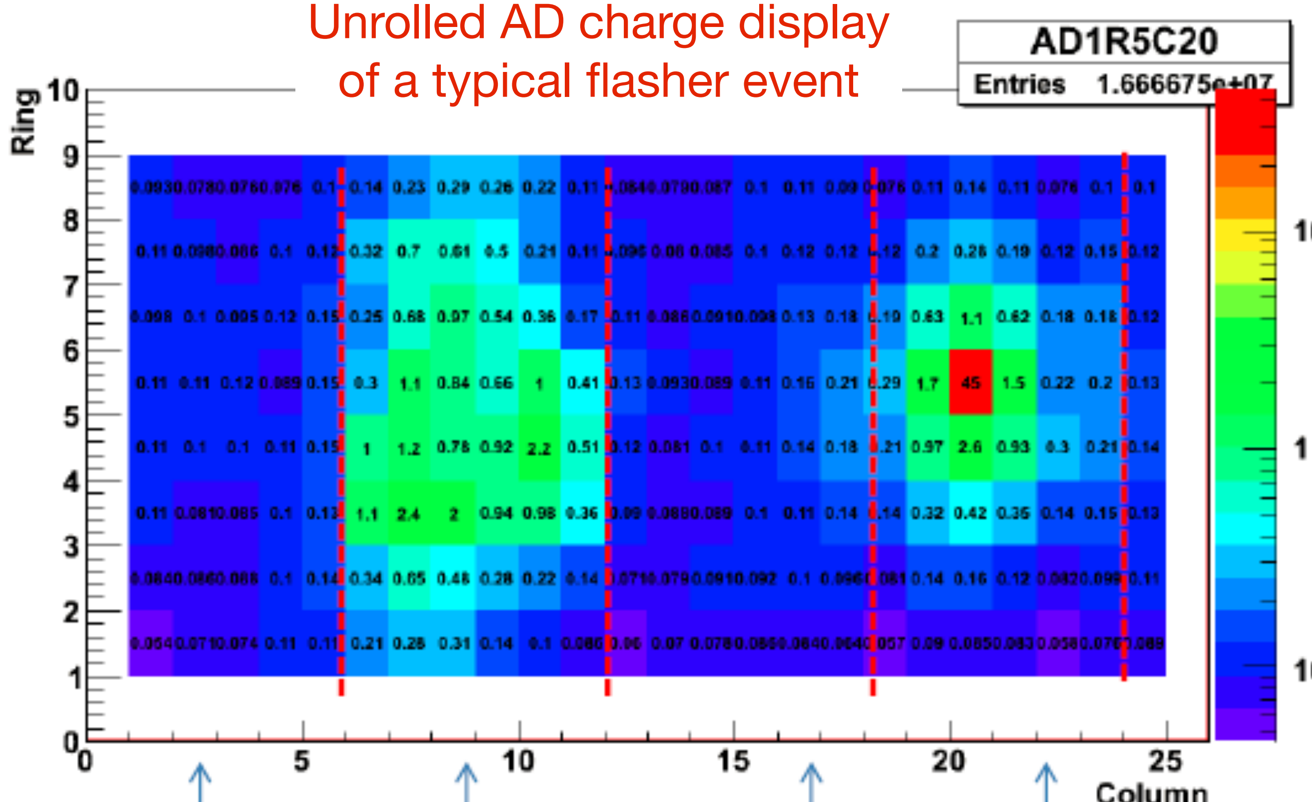


- Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L) + LAB
- > 3 years R&D (BNL&IHEP) and >1 year 1-t prototype monitoring on Gd-LS stability
- Multi-stage purifications on optical improvement and U/Th removal
- 185-ton Gd-LS + 196-ton LS production

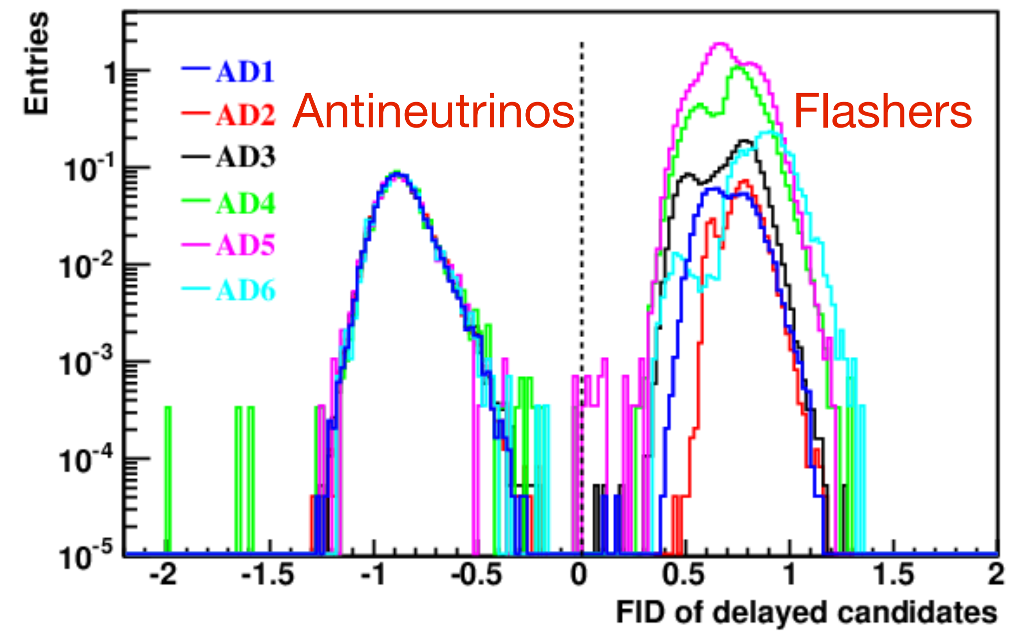
PMT Light Emission (Flasher)

Flashing PMTs:
- Instrumental background from ~5% of PMTS
- ‘Shines’ light to opposite side of detector
- Easily discriminated from normal signals

Unrolled AD charge display
of a typical flasher event



Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1, where the hottest PMT locates



$$\log\left(\left(\frac{Quadrant}{1.}\right)^2 + \left(\frac{MaxQ}{0.45}\right)^2\right) < 0$$

Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

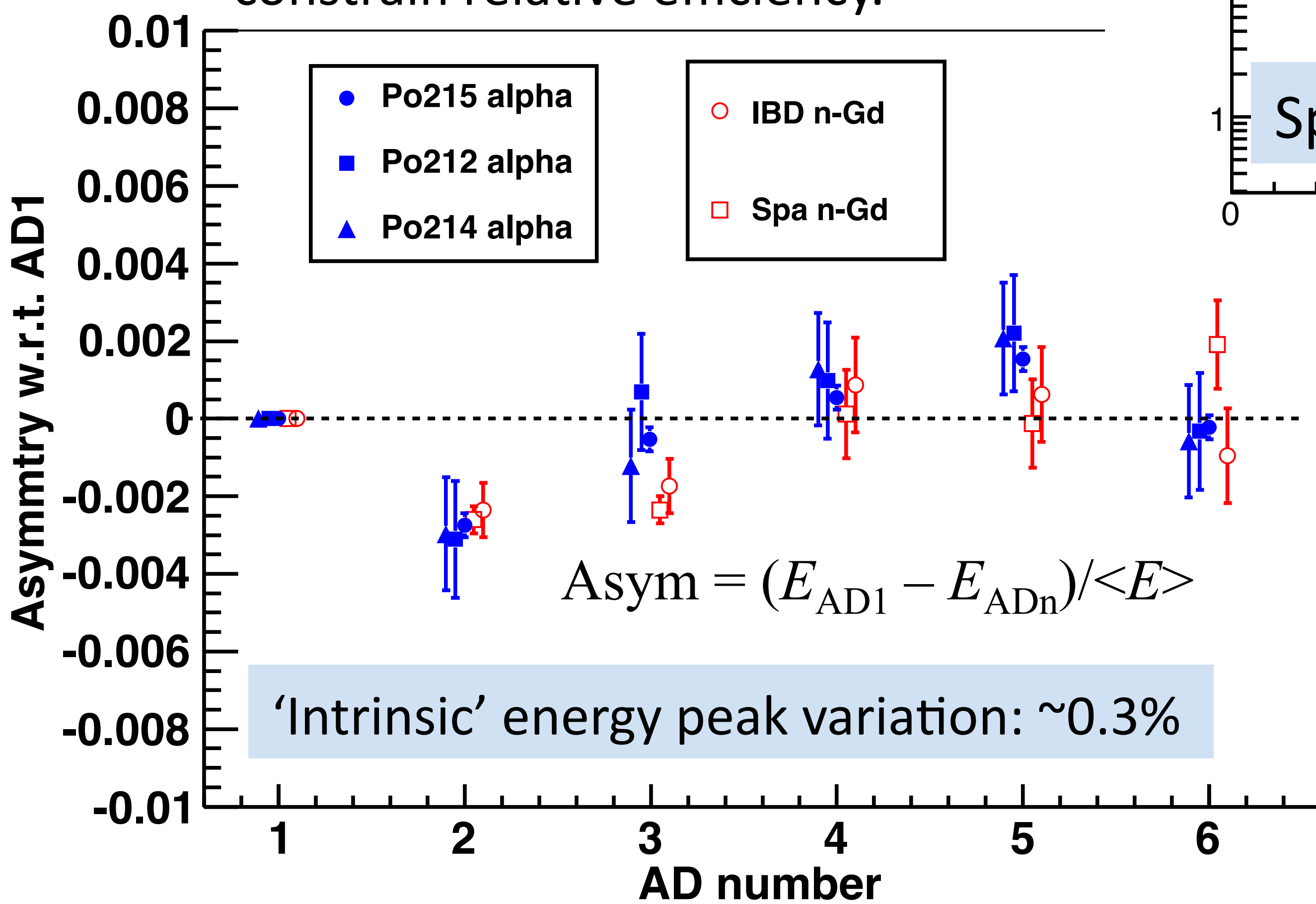
Inefficiency to antineutrinos signal:
0.024% ± 0.006%(stat)
Contamination: < 0.01%

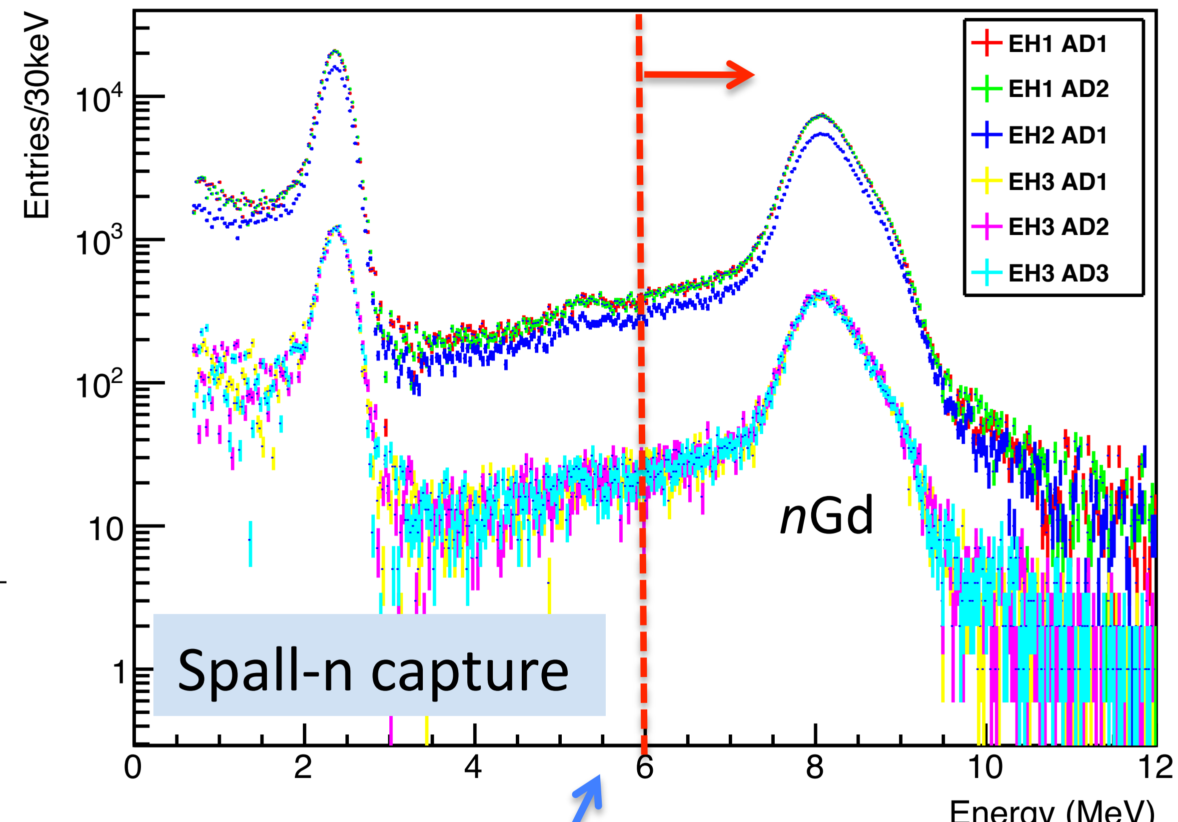
Delayed Energy Cut

Largest uncertainty between detectors

Some *n*Gd gammas escape scintillator region, visible as tail of *n*Gd energy peak.

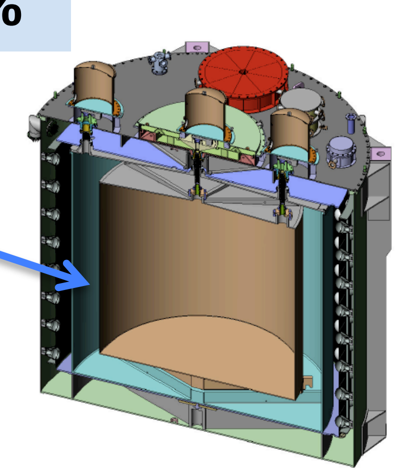
Use variations in energy peaks to constrain relative efficiency.





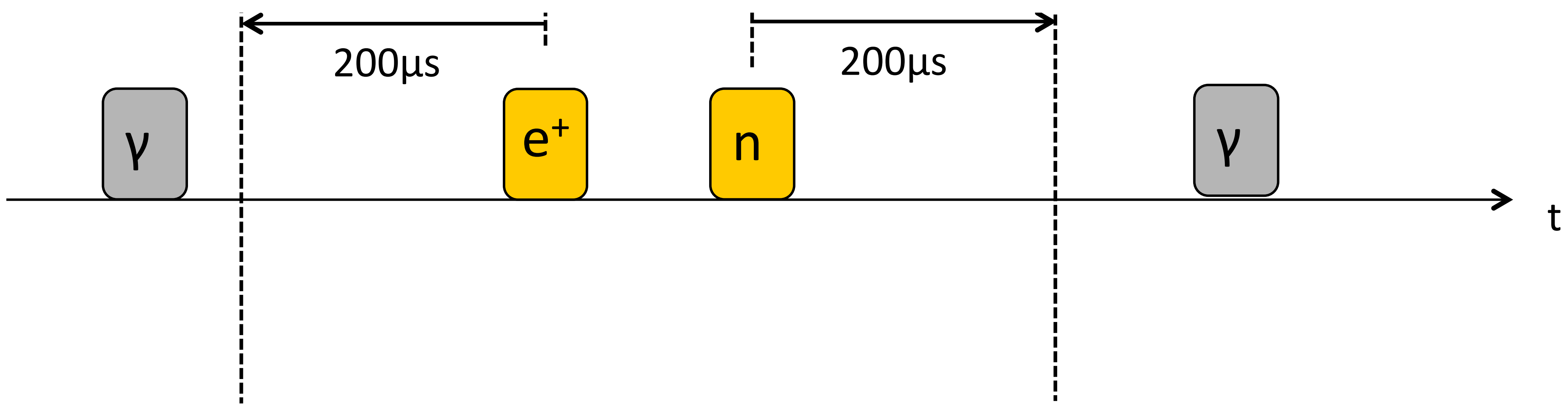
Efficiency variations estimated at 0.12%

Motivation for 3-zone design



Multiplicity Cut

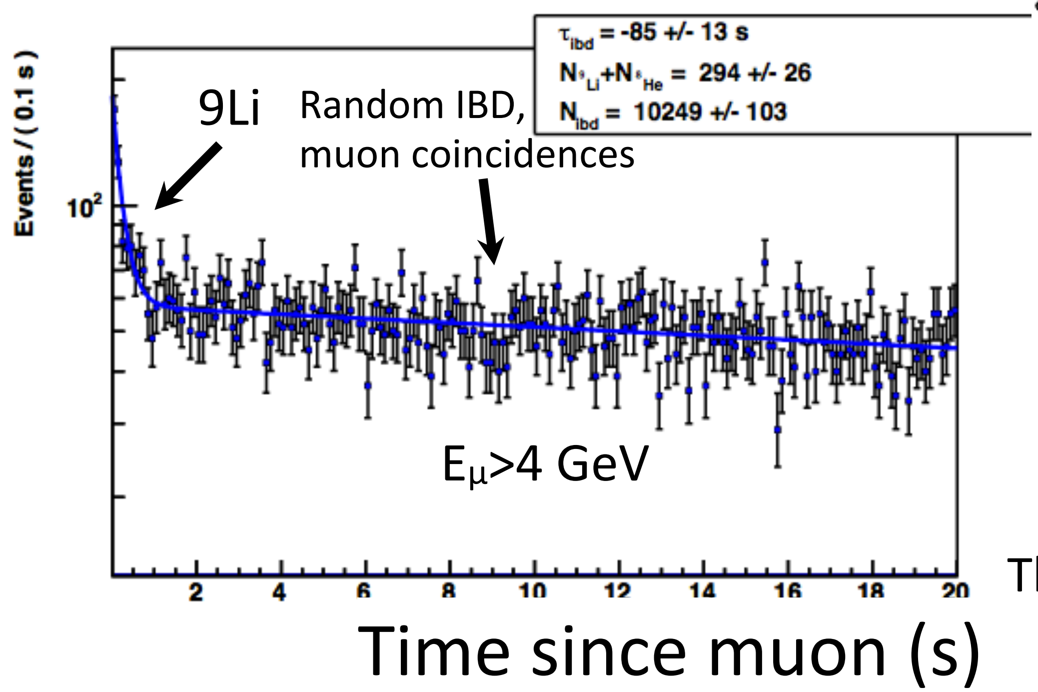
Ensure only one prompt-delayed pair

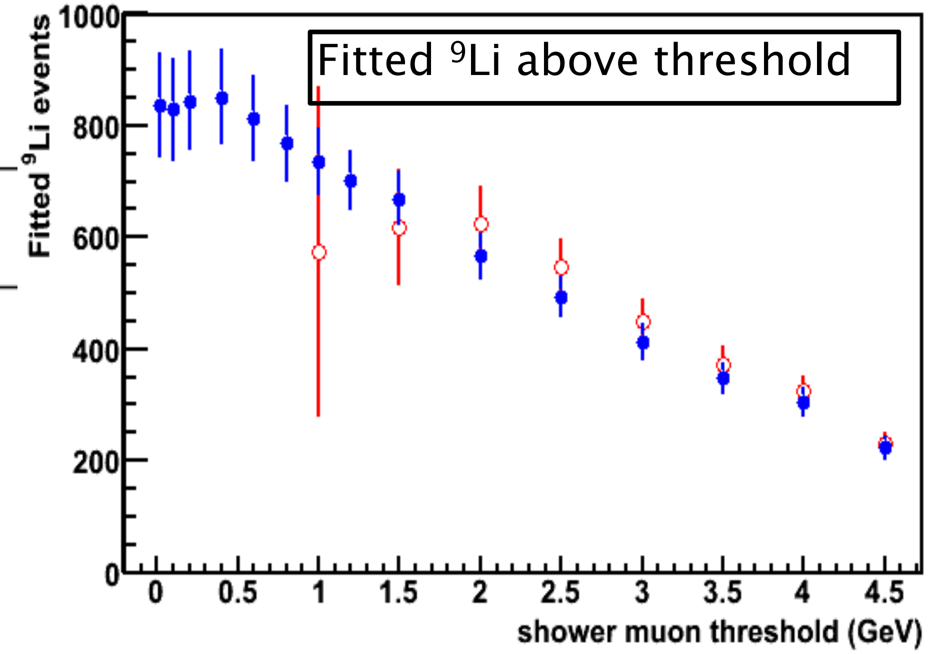


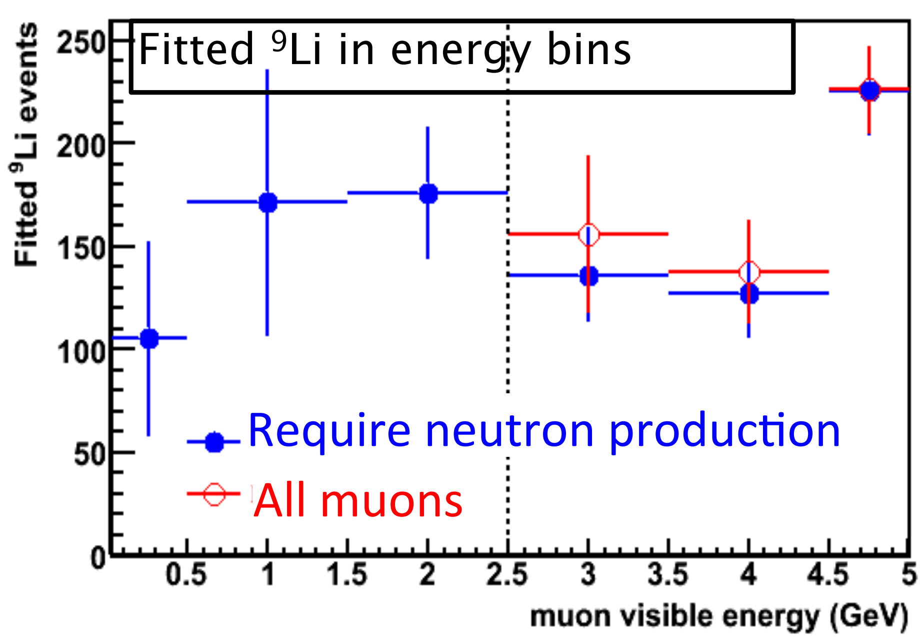
Uncorrelated background and IBD signals result in ambiguous prompt-delayed signals

Reject all IBD with > 2 trigger above 0.7 MeV in -200us to +200us
Introduces ~2.5% IBD inefficiency, with negligible uncertainty

Background: ^{9}Li/^{8}He







The precision of the fitted ^{9}Li rate is given by

$$\sigma_b = \frac{1}{N} \cdot \sqrt{(1+\tau R_\mu)^2 - 1}$$

where R_μ is the muon rate, τ is ^{9}Li lifetime.
Measure 9Li with two selection methods based on the energy deposited in the AD and the detected co-production of neutrons.

1. Muons above an energy threshold
2. Muons in bins of energy

The neutron co- production requirement reduces the muon rate and allows a measurement of the ^{9}Li rate.
Comparison of rates allows uncertainty estimate.

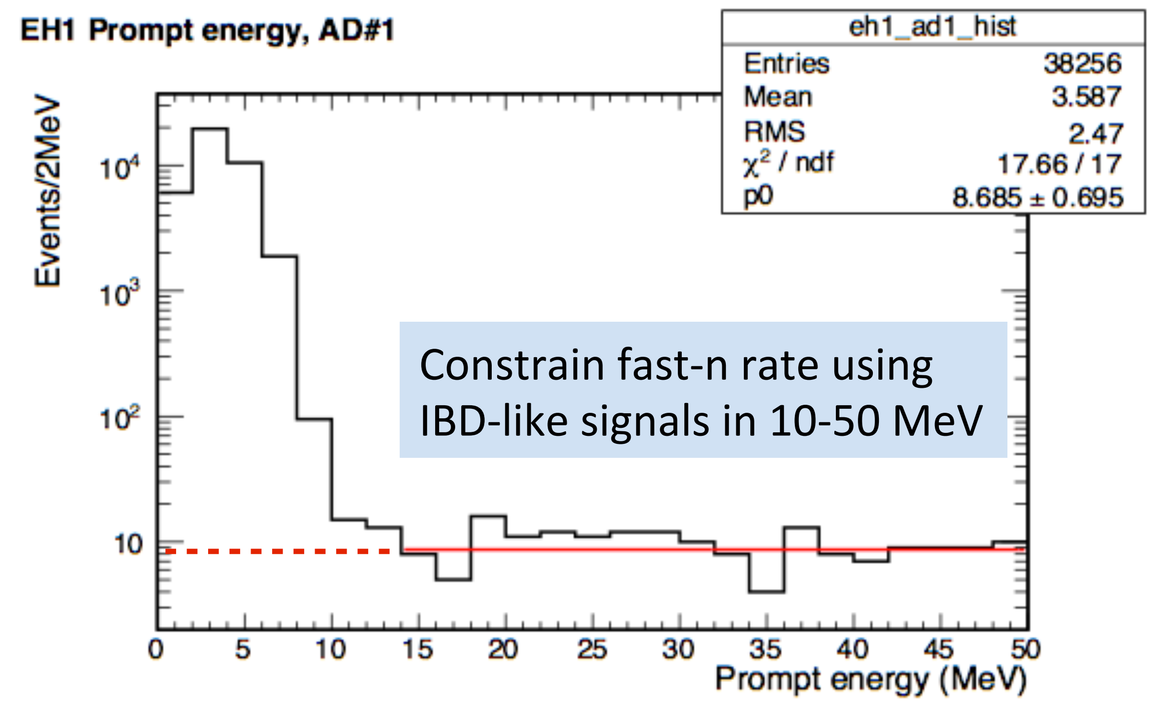
Background: Fast Neutron

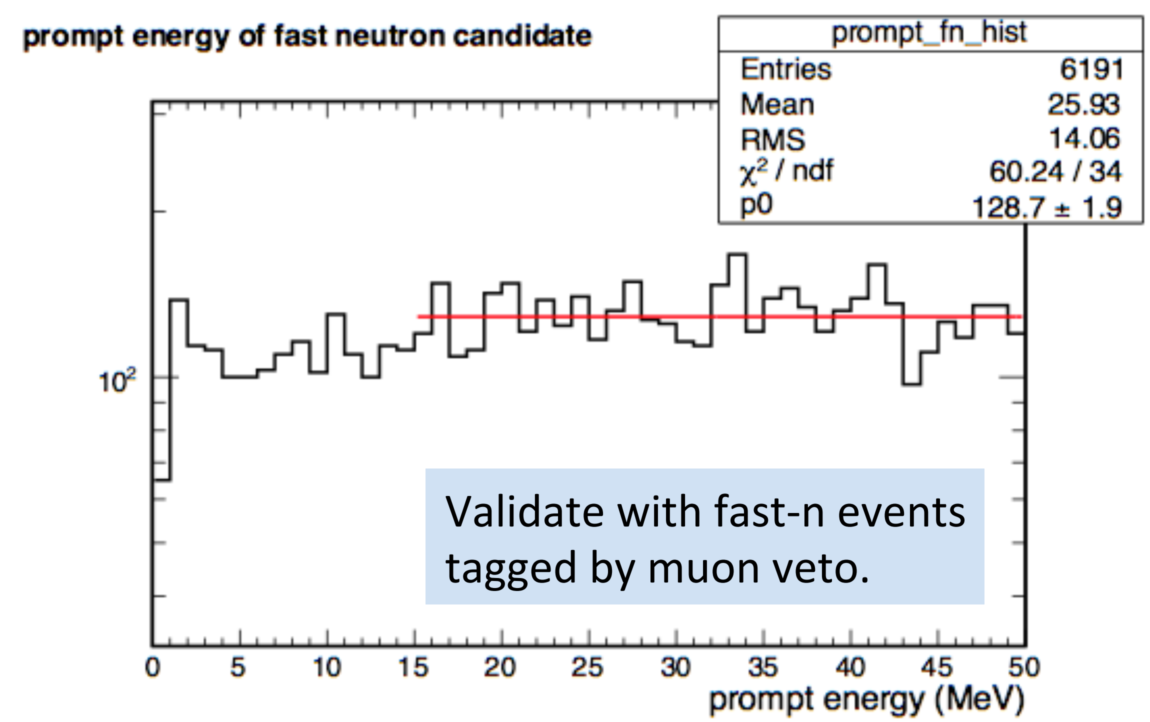
Fast Neutrons:

Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

Mimics antineutrino (IBD) signal:

- Prompt: Neutron collides/stops in target
- Delayed: Neutron captures on Gd

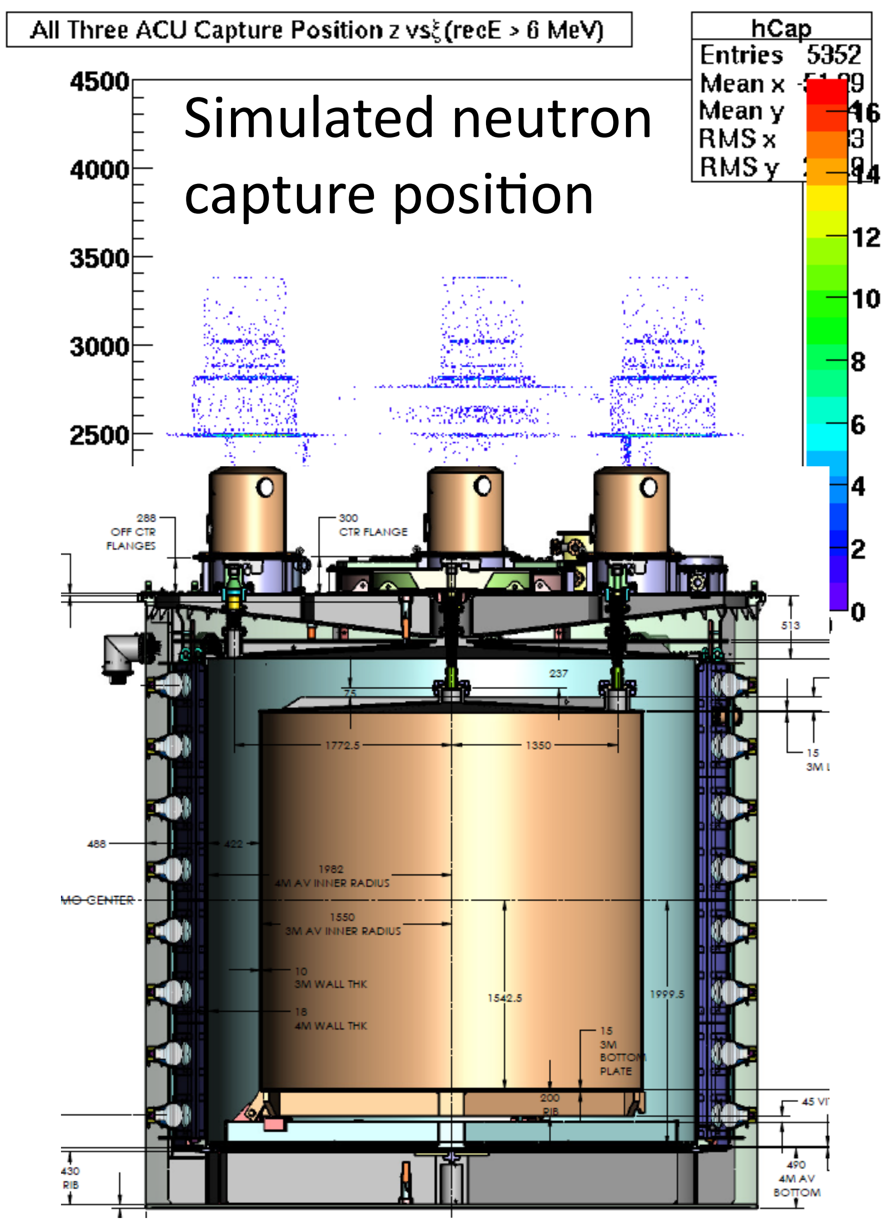


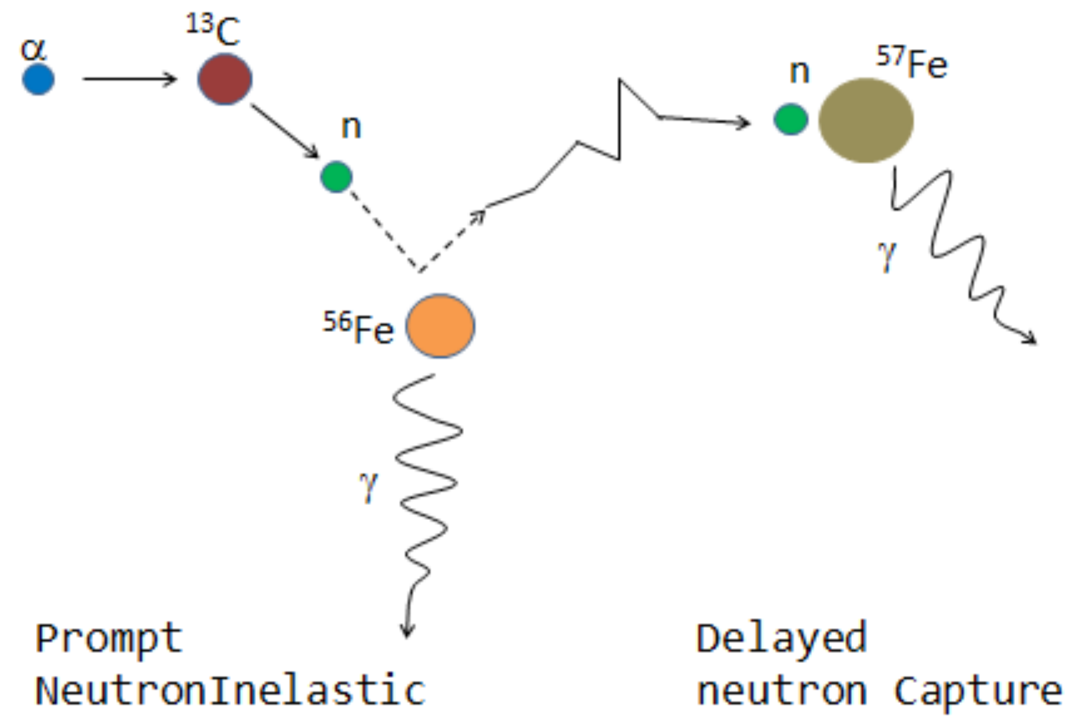


Analysis muon veto cuts control B/S to 0.06% (0.1%) of far (near) signal.

Background: $^{241}Am^{13}C$ Source

Weak (0.5Hz) neutron source in ACU can mimic IBD via inelastic scattering and capture on iron.





Constrain far site B/S to 0.3 ± 0.3%:

- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation

Background: $^{13}C\,(\alpha, n)\,^{16}O$

$^{13}C\,(\alpha, n)\,^{16}O$ — 1.1% natural abundance ^{13}C

- $\rightarrow n + p \longrightarrow n + p$ ①
- $\rightarrow n + {}^{12}C \longrightarrow n + {}^{12}C^*(4.4\ \mathrm{MeV})$
  - $\rightarrow {}^{12}C + \gamma$ ②

$^{13}C\,(\alpha, n)\,^{16}O^*(6.05\ \mathrm{MeV})$

- $\rightarrow {}^{16}O + \gamma$ ③

$^{13}C\,(\alpha, n)\,^{16}O^*(6.13\ \mathrm{MeV})$

- $\rightarrow {}^{16}O + e^+ + e^-$ ④

Example alpha rate in AD1	^{238}U	^{232}Th	^{235}U	^{210}Po
Bq	0.05	1.2	1.4	10

Potential alpha source:

^{238}U, ^{232}Th, ^{235}U, ^{210}Po:

Each of them are measured in-situ:

U&Th: cascading decay of

Bi(or Rn) – Po – Pb

^{210}Po: spectrum fitting

Combining (α,n) cross-section, correlated background rate is determined.

Near Site: 0.04+-0.02 per day, B/S (0.006±0.004)%

Far Site: 0.03+-0.02 per day, B/S (0.04±0.02)%

Reactor Flux Expectation

Anti-neutrino flux is estimated for each reactor core

Flux estimated using:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor operators provide:
- Thermal power data: W_{th}
- Relative isotope fission fractions: f_i

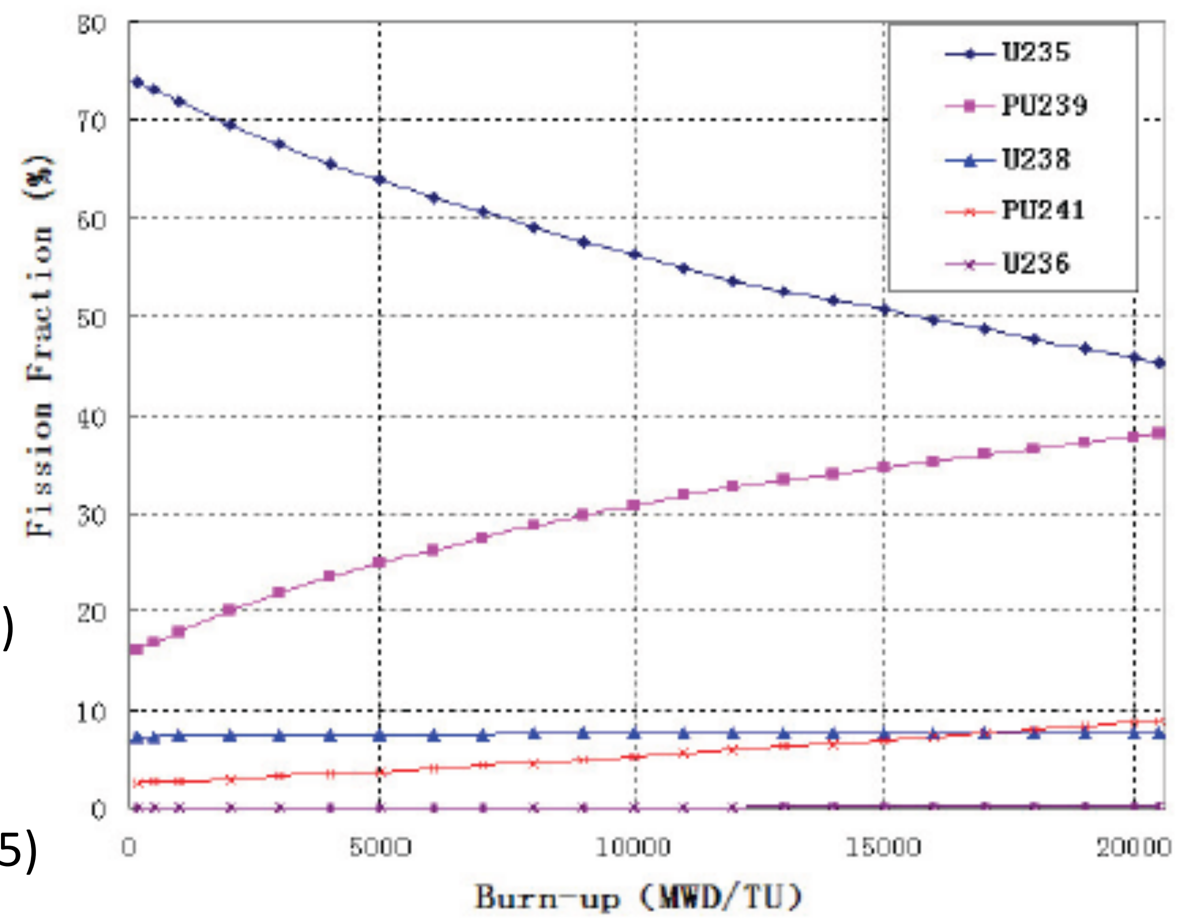
Energy released per fission: e_i

V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

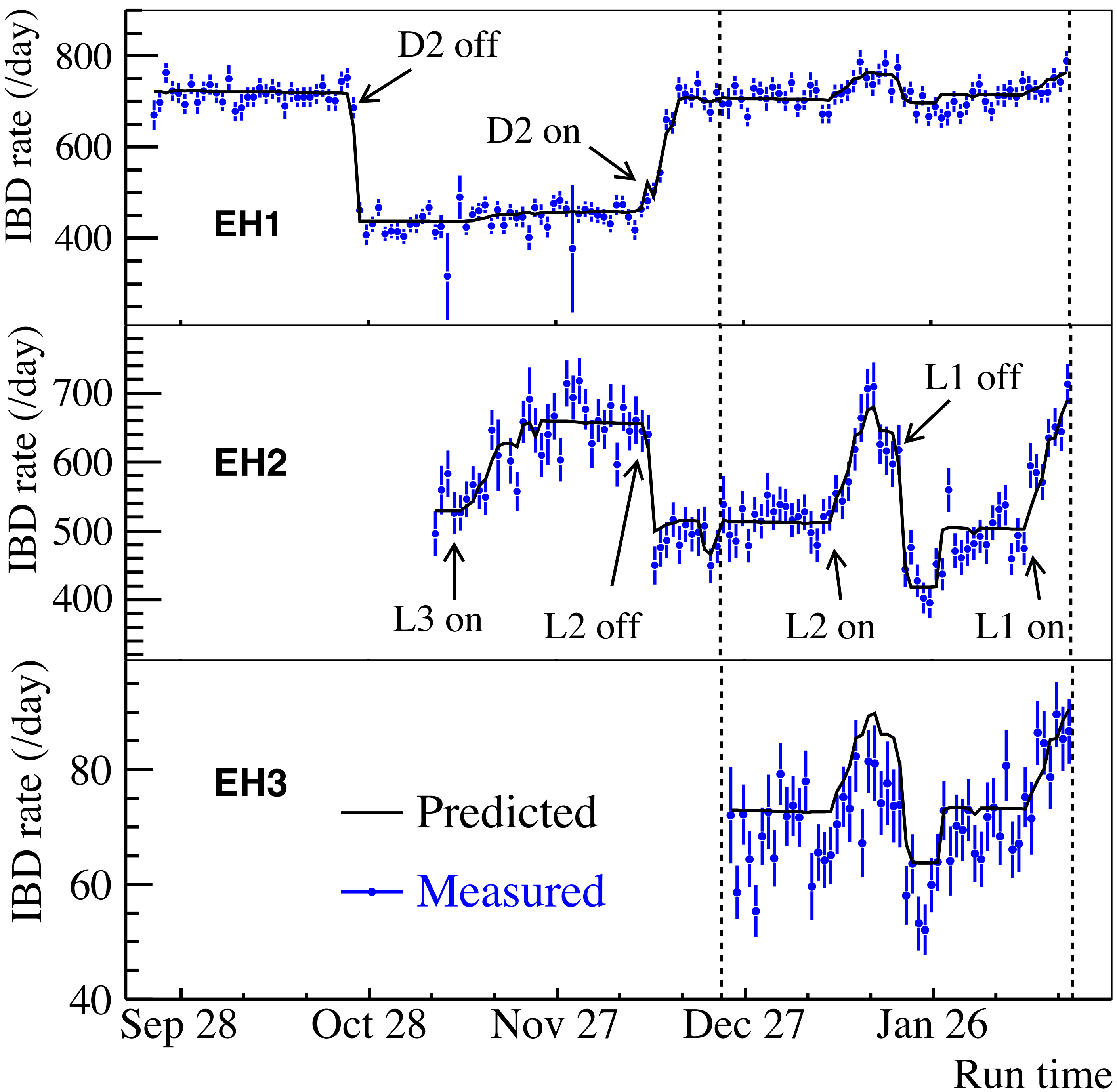
K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

Isotope fission rates vs. reactor burnup



Flux model has negligible impact on far vs. near oscillation measurement

Detected Anti-neutrino Rate vs. Time



Detected anti-neutrino rate strongly correlated with reactor flux expectations

Predicted Rate: (in figure)

- Assumes no oscillation.
- Normalization is determined by fit to data.
- Absolute normalization is within a few percent of expectations.

Full Definition of Chi-square

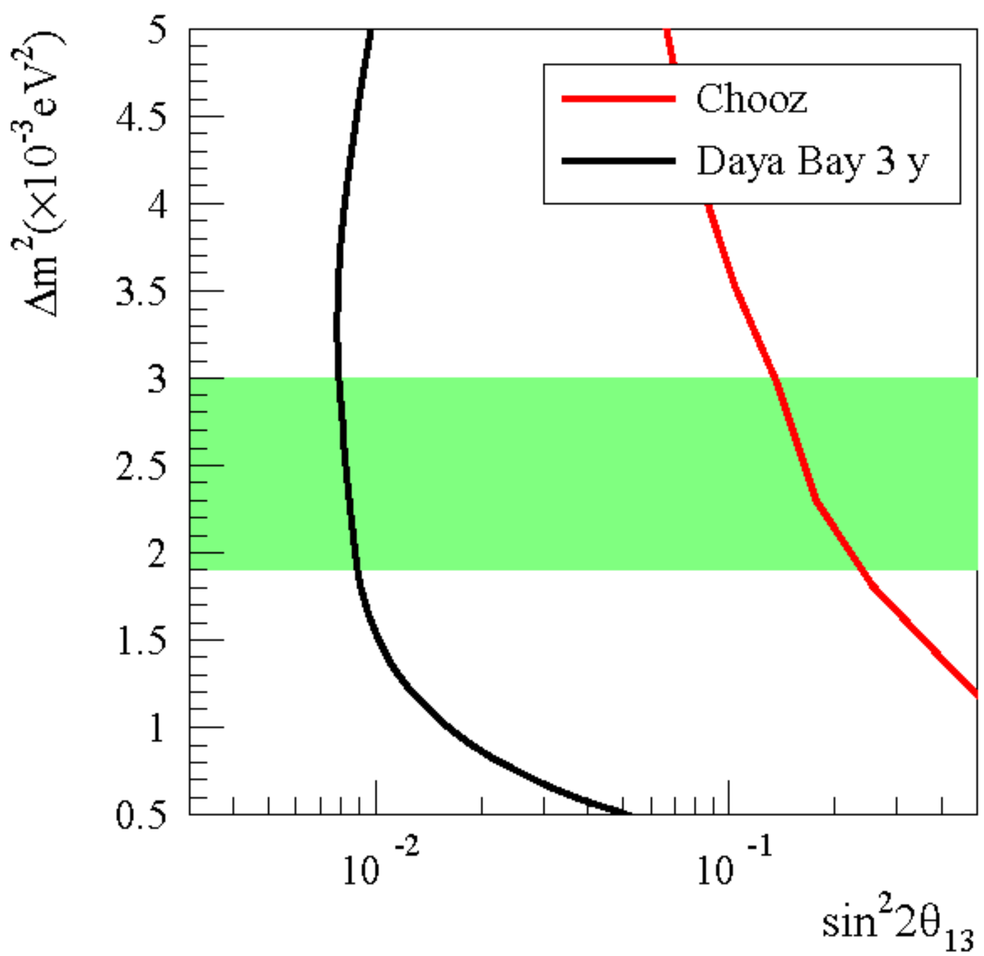
The value of $\sin^2 2\theta_{13}$ was determined with a χ^2 constructed with pull terms accounting for the correlation of the systematic errors [29],

$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d\right) + \eta_d\right]^2}{M_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right), \tag{2}$$

where M_d are the measured IBD events of the d-th AD with backgrounds subtracted, T_d is the prediction from neutrino flux, MC, and neutrino oscillations [30], ω_r^d is the fraction of IBD contribution of the r-th reactor to the d-th AD determined by baselines and reactor fluxes.

Projected Sensitivity

3 Years,
90% Confidence Level



1 Year Of Data Taking = 300 Days